Identifying The Future Research Trend for Using Speed-Controlled Hydraulic Cylinders in Offshore Applications through Literature Survey

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Abstract.

The speed-controlled hydraulic cylinder enhances energy efficiency by removing the control valve throttling, lone pipeline, and HPU losses. Furthermore, it offers energy recovery capability, enables plug-and-play installation, and reduces maintenance. Therefore, it is a promising alternative to the valve-controlled cylinder. This paper surveys the challenges and issues of using the speed-controlled cylinder in offshore applications from the literature and suggests future research trends.

Firstly, the commercial solutions and research done on speed- controlled cylinders are reviewed. The review covers both circuit designs and control algorithms. Speed-controlled cylinders found in the literature are sorted into several classes. Secondly, the research target is selected, and selection criteria are described. Thirdly, the future research trend is discussed. Finally, it is concluded that more research that focuses on high power output levels and system-level (multi-cylinder systems) is needed to show if the technology is feasible for the offshore industry.

Keywords. pump-controlled cylinders, speed-controlled cylinders, linear hydraulic actuation, offshore cranes.

1. INTRODUCTION

As a heavy industry, offshore activities usually involve many high-force operations, such as heavy lifting and pushing, which inevitably require hydraulic cylinders. The valve-controlled hydraulic cylinder (VCC), developed for almost 170 years [1], is still dominating the market and the industry. However, the VCC has a significant shortcoming: poor energy efficiency due to control valve throttling, e.g., a study on the energy analysis of a load-sensing (LS) compact excavator has shown that 35 % of the total system energy is consumed in control valves [2]. Furthermore, the VCC cannot offer energy recuperation capability under overrunning load. Although new designs, such as the independent metering technology, can significantly increase the system's energy efficiency, they cannot fundamentally remove the throttling losses from the system. In addition to throttling losses, offshore VCC systems experience the downside of a central HPU and long pipelines increasing energy losses and the risk of environmental pollution. Therefore, new user-friendly and environment-friendly technologies are needed to remove the throttle loss, offer energy recovery, and keep a similar dynamic performance as the VCC. The speed-controlled hydraulic cylinder (SCC) is one of these technologies.

As a promising technology to replace the VCC, the SCC enhances energy efficiency by removing the control valve throttling, lone pipeline, and HPU losses. Furthermore, it offers energy recovery capability, enables plug-and-play installation, and reduces maintenance. The SCC is a sub-branch of the pump-controlled cylinder (PCC). A simplified diagram of the PCC is shown in Fig. 1. In a PCC, One or two ports of the cylinder are connected to hydraulic pump(s) and the reservoir through auxiliary valves; auxiliaries valves are used for safety reasons, compensating for the differential flow rates, and changing flow directions; an accumulator or an open tank works as the reservoir.

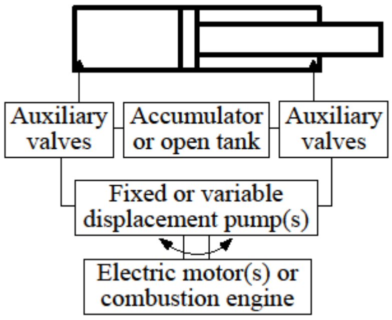


Figure 1. Structure of a PCC.

In a PCC, when the oil in the rod side of the cylinder can flow to the piston side without passing through the reservoir, it is called a closed-circuit PCC. Otherwise, it is called an open-circuit PCC. In PCCs, controlling the cylinder motion is equivalent to controlling the pump's flow rate. There are two ways to control the pump's flow rate in a PCC: using the variable-displacement pump(s) driven by the constant-speed prime mover(s), which can be called the displacement-controlled cylinder (DCC); using the fixed-displacement pump(s) driven by the variable-speed prime mover(s), which can be called the speed-controlled cylinder (SCC).

The pump-controlled technology initially started from displacement-controlled symmetrical actuators. It was firstly used for controlling super high power hydraulic motors in the early times [3]. Then it was used to control a double rod cylinder [4]. The single-rod DCC was intensively researched and developed around the 2000s but almost exclusively for non-road mobile machinery because an internal combustion engine is often used as the only prime mover [5]. However, DCCs have some shortcomings compared with SCCs, such as variable-displacement pumps are more expensive and less efficient than fixed-displacement pumps under partial load [6], [11], [25]; the prime mover in idling mode causes energy losses, noise, and extra heat [6]; the swashplate control systems and external low-pressure source undermine the system compactness and increase the energy losses. Therefore, academia and industry are paying less and less attention to DCCs and putting more weight on SCCs [7].

The electrification trend of hydraulic systems and the development of electric servo motors enhanced the development of SCC. Historically, SCCs emerged in the aircraft industry for primary flight control in the early 1990s driven by the concept of power-by-wire [8], [9]. Nowadays, SCCs are widely used in different industries due to their high energy efficiency, compact structure, plug-and-play installation, reduced maintenance, low noise level, and control by frequency converters instead of control valves [7], [8], [10], [11].

Electro-mechanical cylinders (EMCs), another drive technology encouraged by electrification, have some advantages similar to SCCs, such as a similar efficiency range, high degree of user-friendliness and compact design [12]. However, SCCs are still superior to EMCs in several features. SCCs generate higher forces, have better acceleration performance, absorb more impacts, and can be operated at higher speeds [12]. For heavy operations, SCCs are more energy-efficient, have lower weight and cost, and are easier to complete with security features [11]. SCCs have higher continuous power capability, less installed electric power, longer expected service life, and less overall mass [13].

2. State of the Art of SCC

In this section, the state of the art of SCCs is categorized into five parts: SCC architectures, SCC controls, SCC thermal analysis, other SCC topics, and identified research gaps.

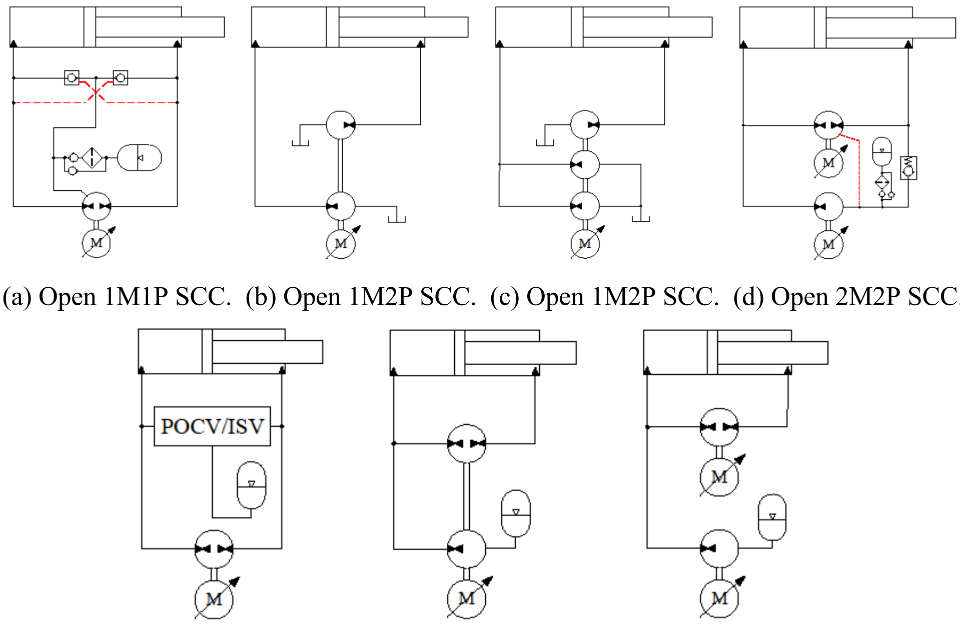
2.1. SCC Architectures

In terms of the number of electric motors and hydraulic pumps used, SCC architectures can be classified into four groups: one-motor-one-pump (1M1P), one-motor-two-pumps (1M2P), one-motor-three-pumps (1M3P), and two-motors-two-pumps (2M2P) SCCs. Simplified SCC diagrams within these four groups are shown in Fig. 2.

2.1.1. 1M1P SCC

The 1M1P SCC was initially developed for driving double-rod cylinders used in the aerospace industry [9] but has since then expanded into many other industries [7]. The advantage of double-rod SCCs is that there are no differential flow rates in the circuit. Therefore, the hydraulic circuit is simpler. Other research works on double-rod SCCs can be found: In [14], a double-rod SCC was tested and evaluated on the F-18 research aircraft; In [15], the deadband issue of a double-rod SCC was investigated; In [16], double-rod SCCs were implemented on a train as tilt actuators; In [17], A double-rod SCC with a power regulator was proposed.

80 % of cylinders used in the industry are single-rod cylinders, especially in heavy industries [18]. Therefore, most works on SCCs are about single-rod SCCs. An in-depth numerical and experimental comparison between a SCC and a load-sensing VCC in motion control and energy efficiency aspects was presented in [19], [20]. The SCC has significantly better control performance, such as 75 % shorter settling time, 61 % less overshoot, 66 % better position tracking, reduction of pressure oscillations, and remarkably consumed 62 % less energy.



(a) Open 1M1P SCC. (b) Open 1M2P SCC. (c) Open 1M2P SCC. (d) Open 2M2P SCC.

(e) Close 1M1P SCC. (f) Close 1M2P SCC. (g) Close 2M2P SCC.

Figure 2. SCC structures

System-level implementation is important for investigating the all-around performance of SCCs. A system-level simulation study of implementing three 1M1P SCCs on a pipe racking machine was shown in [21]. Simulation results demonstrated that the new SCC system consumed 83.4 % less energy than the VCC system if the energy recuperation function was considered. Another system-level comparative research of implementing six 1M1P SCCs on an excavator was presented in [22]. The simulation showed maximum 75.1 % energy saved by SCCs, and experimental results showed 47.8 % energy saved by SCCs compared with VCCs.

An inverse shuttle valve (ISV) or two pilot-operated check valves (POCV) are often used to compensate for the differential flow rates in single-rod SCCs. However, these two methods suffer from mode oscillation under certain operating conditions. Mode oscillation in an SCC using an ISV was analysed in [10]. The author presented a new approach to describe the dependence between the inertial load (the acceleration rate) and the occurrence of mode oscillation. In the study [23], it was revealed that a partially open ISV is required in an unstable load pressure region during actuator retracting to prevent mode oscillation. Therefore, an elaborate underlapped ISV was proposed and validated by numerical and experimental tests. Instead of using two POCVs, two digital on/off valves were proposed to suppress mode oscillation when compensating for the differential flow rates in an SCC [24].

Standard hydraulic pumps are designed to run above a minimum speed because it is difficult to provide a durable lubrication film between the working parts inside the pump [6], [9]. However, hydraulic pumps used in SCCs may be operated at high pressure and low or nearly zero speed. A closed- circuit SCC using a 2/2 proportional valve as a bypass valve (BPV) was proposed to address the low-speed challenge and compared with its open-circuit counterpart in [25]. The BPV connects two ports of the differential cylinder and increases the pump speed when the cylinder is moving slowly. Simulation results showed that the BPV undermined the two systems' energy efficiency in low-speed working modes. The open-circuit SCC has higher energy efficiency than the closed- circuit counterpart because the two-quadrant pump used in the open-circuit SCC has higher efficiencies than the four-quadrant pump used in the closed-circuit SCC. Furthermore, both architectures could regenerate up to 81.8 % of the actuator energy under overrunning load and achieve an energy efficiency level of 84.7 % [25].

2.1.2. 1M2P SCC

A closed-circuit 1M2P SCC with an accumulator on each side of the cylinder was implemented on a modern flight training simulator [26]. The calculation results and experimental measurements showed that the power consumption was significantly reduced from 45 kW to 5 kW while retaining the same dynamic performance as the VCC. This circuit design requires the displacement volume ratio of the pumps to match the piston area ratio of the cylinder [26].

An open-circuit 1M2P SCC design was proposed and analysed in [27]. Experiment results revealed that the retracting efficiency is low due to no energy recuperation function and the mismatch between pumps' size and the cylinder area ratio. To investigate the energy efficiency of this 1M2P SCC at the system level, a simulation study of implementing three 1M2P SCCs on an excavator with digital on/off valves for load-holding was presented in [28]. Simulation results showed that the overall efficiency of this SCC excavator could achieve 73.3 %, which is much higher than the VCC excavator [28].

An open-circuit 1M2P SCC, which incorporates an anti- cavitation system and two proportional valves used for bleeding off the excessive pressure was modelled, analysed, and experimentally verified in [29]. Experimental results demonstrated that the proposed SCC could maintain a non-load carrying pressure of 25 bar which can secure a satisfactory dynamic performance. The simulation study [30] proposed six different SCCs (four 1M2P and two 1M1P) with self- locking functions. The pressure levels could also be controlled in these new architectures but introduced a delay-like issue and excessive power consumption in static load carrying situations. Furthermore, the proposed SCCs cannot recuperate energy. Low speed and high load working conditions of SCCs were considered in [31], where a proportional bleed-off was introduced to increase the shaft speed when the cylinder speed is running low.

Implementing one isolated 1M2P SCC to every cylinder is not the most feasible idea concerning efficiency and the system flexibility [32]. Three SCC networks were designed and numerically implemented on a knuckle boom crane. Simulations showed that proposed drive networks may improve the energy efficiency and control performance compared with isolated 1M2P SCCs [32].

2.1.3. 1M3P SCC

Based on the 1M2P SCC in [29], a redesigned 1M3P SCC was proposed in [33]. In this 1M3P SCC, the cylinder area and pump displacement ratios were deliberately mismatched to cause pressure build-up or cavitation in the return chamber. The third gear pump supplies one- way flow to avoid the caused cavitation. Simulation results showed that this redesigned 1M3P SCC has a similar tracking performance as a VCC, but much higher energy efficiency [33]. Later, an in-depth controller design of this over-actuated 1M3P SCC was proposed in [34].

2.1.4. 2M2P SCC

The investigation of applying closed- circuit 2M2P SCCs on plastic injection moulding machines can be found in [6], [35]. Furthermore, the study [35] reported two advantages of the closed-circuit 2M2P SCCs: the insensitivity of cylinder velocity to load pressure change and the capability of amplifying the load pressure by pump revolution. A VCC, a closed-circuit 2M2P SCC, and an open-circuit 2M2P SCC were numerically compared in energy efficiency in [36]. Simulation results demonstrated that the two proposed SCCs have much higher energy efficiency than the VCC. Moreover, the closed-circuit 2M2P SCC is more efficient, more cost- effective, and requires a smaller reservoir than the open-circuit one. A 2M2P SCC with load-holding functions was proposed and investigated in [37]. Simulation results demonstrated good performances in motion control, pressure level control, and load-holding.

2.2. SCC Controls

SCCs are characterized by low system damping, leading to mechanical structure oscillations. This shortcoming can be addressed by adding active damping via either pressure or acceleration feedback. These two approaches were implemented in a 1M1P SCC driving robotic manipulators [38]. Simulation results demonstrated that both approaches could greatly improve the system damping. Research on pressure feedback can also be found in [39].

When introducing more control elements into SCCs, such as extra electric motors and hydraulic pumps, the system output power is increased, and the pressure level can be controlled. However, it involves complicated multi-input-multi-out (MIMO) controls. A novel MIMO controller used for controlling the cylinder motion and pressure level in an over- actuated 1M3P SCC was proposed in [34], and the relative gain array (RGA) method was used for the state coupling analysis. The RGA method was also adopted to develop a MIMO controller for controlling the motion, backpressure, and temperature in a 1M2P SCC [40]. The experimental verification showed that another control input is needed for a cooler, and the decoupled pressure control needs to be improved [40]. Furthermore, the RGA method was used in the MIMO controller design for a 2M2P SCC with a load-holding function [37] and a 2M2P SCC using a bootstrap reservoir [41], [42].

2.3. SCC Thermal Analysis

Based on a heat resistance network, a thermo-hydraulic model of a 1M1P SCC was developed to predict the thermal energetic behaviour and secure a stable temperature operation [43]. The influence of temperature in the range of 910 to +22 ◦C to a 1M2P SCC prototype was investigated in [44]. Experiments with the thermal camera showed that the change of the outside temperature influenced the system's energy efficiency. Furthermore, a thermo-hydraulic model of a 1M2P SCC was developed in SimulationX and validated against experimental measurements utilizing thermocouples and the thermal camera [45]. A lumped thermo-hydraulic model of a 1M1P SCC was derived and verified against experimental measurements [46]. It was revealed that the dynamic pressure- temperature coupling could be neglected; an elaborate thermal resistance network offers better temperature predictions than a simple model [46].

2.4. Other SCC Topics

Self-contained SCCs often use a gas accumulator as the reservoir. However, for high power level SCCs, the size and mass of the gas accumulator are significant, which may affect the system. Using a bootstrap reservoir instead of a gas accumulator can greatly downsize the reservoir [47]. However, strong state couplings were found when the bootstrap was introduced in 2M2P SCCs [41], [42].

In a self-contained SCC, all components are often mounted together, leading to the electric motor, hydraulic pumps, and accumulators being extra weights to the cylinder, which may affect the machine structure and the system's performance. This issue was investigated in [48] via finite element analysis and simulations of an excavator. Simulation results demonstrated that the extra weights do not significantly affect the excavator structure. If the energy recuperation was assumed, the increased energy consumption related to the increased mass was about 12 %. A study on the mass effects of self- contained SCCs used on a knuckle boom crane was presented in [49]. This paper concluded that the chosen SCCs only reduce the payload capacity in the range from 0.8 % to 2.1 % according to different work scenarios.

Prime movers in high-power SCCs are usually oversized to meet the peak power requirement. A hybrid system, consisting of an SCC and an energy storage system, was proposed in [50] to shave the power peak and downsize the prime mover. Compared with the nonhybrid system, the hybrid system only requires a prime mover with 70 % less installed power with- out degrading the control performance; however, the system compactness and cost are compromised [50].

SCCs are usually self-contained systems using an accumulator as the reservoir, leading to wear and contamination sensitivity. Endurance tests of a 1M2P SCC were presented in [51], where oil samples were periodically taken, and visual inspections evaluated the pump wear. Test results demonstrated that although the hydraulic pump was robust against the high particle load, SCCs could not be driven without a filter. In [31], the wear rate of the journal bearing of the gear pump used in a 1M2P SCC was analysed based on the Ocvirk Number and Archard's Wear Law, and a wear-reducing control was proposed, which, however, induces extra losses.

2.5. Identified Research Gaps

Most of the research on SCCs is done at a single drive level and low power level. High power level (over 200 kW) and system-level research, where the hydraulic power can be shared and exchanged among multiple drives and recyclable, have not been identified.

3. IDENTIFY THE RESEARCH TARGET

According to the research gaps identified in II-E, the research target should have high power output and power consumption and comprise multiple cylinders. Furthermore, it should involve control challenges, e.g., automation and four-quadrant operations. In an offshore hydraulic machine survey conducted by the author, the Pipe Handling Crane (PHC) is the only one that meets all the conditions above. In a PHC, as shown in Fig. 3, there are one or two cylinders in parallel driving the main boom, one cylinder driving the knuckle boom, one cylinder driving the telescope, and two hydraulic motors driving the slew motion.

Figure 3. A PHC from National Oilwell Varco. ©

The knuckle boom cylinder's piston velocity and load force vary independently between negative and positive during operation. Therefore, the knuckle boom cylinder is operated in four quadrants. The main boom and telescope cylinders are operated in two quadrants because their load forces never change directions. The PHC is used to lift and move heavy tubular loads on drilling ships and platforms, such as drill pipe, drill collar, and casing. A PHC from *National Oilwell Varco* with product number PC1891K is chosen as the research target. Its maximum load capacity is 12 t, and its maximum input power is 259.6 kW. It has long working hours because it continuously delivers drill pipe between the pipe deck and the catwalk machine during the entire offshore drilling operation.

4. Discussion

Compensating for the differential flow rates is still one of the main challenges for closed-circuit 1M1P single-rod SCCs. POCVs or an ISV can be used to compensate for the differential flow. However, they suffer from mode oscillation under certain loads and working conditions. Mode oscillation is unacceptable to large offshore cranes due to safety requirements. Most approaches in the literature preventing mode oscillation are control approaches. Therefore, the future research trend of closed-circuit 1M1P single-rod SCCs used offshore could focus on new architectures that can compensate for the differential flow without triggering mode oscillation under all load conditions and at the same time consider circuit simplicity. Although the low operating speed issue in 1M1P SCCs can be addressed by adopting a bypass valve [25], the system energy efficiency is compromised. Therefore, there is a need to explore more efficient designs in this regard.

1M2P SCCs can compensate for the differential flow rates without triggering mode oscillation. However, the two pumps' displacement ratio must match the cylinder area ratio, limiting universal availability. The open-circuit 1M2P SCC has a lower power transmission ratio, leading to oversized prime movers. Low drive stiffness is common for one prime mover SCCs, mainly due to the system's low damping ratio and the low backpressure. Adopting extra control valves [30] or pumps [34] improves the drive stiffness. Nevertheless, these methods are rather complicated and costly for broadly offshore use. Future research on one prime mover SCCs used offshore should focus on control methods, such as adding active damping [38], and new architectures that can realize the backpressure control without increasing the circuit complexity and cost.

The closed-circuit 2M2P SCC is the best SCC architecture for offshore applications. It offers the best scalability, the insensitivity of cylinder velocity to load pressure change, a relatively simple circuit structure, and system pressure level control. Its future circuit designs should consider coping with high power output at low operation speeds, common for offshore high-power cranes. Furthermore, the 2M2P SCC re- quires sophisticated MIMO control. However, only the MIMO control design with the RGA method has been identified. Other methods should be explored in future research.

The electric motor, pump, and accumulator are often mounted together with the cylinder when implementing SCCs on applications. It might be an issue for offshore applications. For example, the PHC has long cylinders driving long beams, and the cylinders are far from the deck and operation room, which is inconvenient for maintenance. When cylinders are retracted, there might not be enough space for components attached to cylinders. Moreover, the weight of the electric motor, pump, and accumulator causes extra energy consumption, especially when the energy recovery device is not in place. Therefore, future research on offshore SCCs should explore alternative layouts and compare the differences.

Implementing isolated SCCs on a large system is not always practical and energy efficient. SCC networks [32] can improve the energy efficiency and control performance and might shave the power peak for a single SCC due to the hydraulic power can be shared among SCCs. Therefore, future research on offshore SCCs should also explore and implement more possible SCC networks.

5. CONCLUSION

This paper presented a literature review of speed-controlled cylinders, a description of a chosen research target, and a discussion about future research on using speed-controlled cylinders in offshore applications. It is concluded that more research that focuses on high power output levels and system- level (multi-cylinder systems) is needed to show if the technology is feasible for the offshore industry.

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