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Programmable Valves Enable Both Precision Motion Control and Energy Saving

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***Abstract*.** Conventional electro-hydraulic precision motion control systems are controlled by either servo valves or proportional directional control valves. Neither of the valves are able to control the pressures at the two cylinder chambers independently or to use the regeneration flow. The result is that while precision motion control is possible, significant energy saving is not. In order to save energy while maintaining excellent motion performance, the independent control of the pressures at the two cylinder chambers and the accurate use of the regeneration flow are two key factors. The programmable valves, a combination of five independently controlled poppet-type cartridge valves, break the mechanical linkage between the meter-in and meter-out orifices, maintain the full functionality of conventional four-way valves and enable the accurate control of the regeneration flow via the true cross port valve. Therefore, the programmable valves are capable of both precision motion control and significant energy saving. This paper introduces the configuration of the programmable valves as well as how to control the programmable valves to achieve the dual objectives of precision motion control and energy saving.

Keywords. Precision Motion Control, Energy Saving, Programmable Valves, Regeneration Flow.

Introduction

The modern control techniques have significantly improved the performance of electro-hydraulic systems. A new problem arises as the applications of electro-hydraulic systems becoming increasingly widespread: is it possible to reduce the energy usage while keep the desired precision motion control performance?

The hydraulic energy used for a certain task can be defined as:

$$E = \int_{t_0}^{t_1} P_s(\tau) Q_s(\tau) d\tau \tag{1}$$

where E represents the hydraulic energy used for a task defined on the time interval from t_0 to t_1, P_s the hydraulic supply pressure and Q_s the pump flow rate. It is obvious that there may be two ways to reduce the energy usage:

1. reduce the supply pressure $P_s(t)$
2. reduce the pump flow rate $Q_s(t)$

Neglecting the fluid compressibility, the pump flow rate depends entirely on the task to be performed unless the regeneration flow is used. To reduce the supply pressure, the pressures at the two cylinder chambers are desired to be as low as possible while certain pressure difference has to be maintained to perform the required motion task. Therefore, the independent control of the two chamber pressures and the use of the regeneration flow are the two keys for energy saving.

Traditionally, a typical four-way directional control valve or a servo valve is used to control a hydraulic cylinder as done in almost all existing publications (Merritt, 1967, Tsao, 1994, Bu and Yao, 2000, Yao et al., 2000). With such a configuration only one of the two cylinder states, (i.e., the pressures of the two chambers), is completely controllable and there is a one-dimensional internal dynamics. Although the internal dynamics is proven to be stable (Bu and Yao, 1999), it can not be modified by any control strategy. The control input is uniquely determined once the desired motion is specified, which makes the individual regulation of the pressures in the two cylinder chambers impossible for energy saving. The result is that while high performance tracking can be attained, simultaneous high level of energy saving cannot.

The programmable valves are proposed to fully take advantage of the decoupled meter-in and meter-out flows and the true cross port regeneration flow. The programmable valves are an unique combination of five independently controlled proportional poppet type cartridge valves, which are known as the economical alternatives to large proportional valves (Ulerly, 1990). The resulting programmable valves are hence capable of controlling each cylinder state as well as providing the fully controlled regeneration flow for maximal energy saving.

Programmable Valves Configuration

The configuration of the programmable valves (Liu and Yao, 2002) is shown in Fig. 1. It is obvious when valve #2 and #5 are open, the programmable valves work similarly as a conventional four-way valve to provide the positive meter-in and meter-out flows; moreover the meter-in and meter-out flows are decoupled because they are controlled by different valves. When valve #1 and #4 are open, the configuration can provide the negative decoupled meter-in and meter-out flows. When valve #3 is open, this configuration is capable to utilize the cross port regeneration flow provided that the necessary pressure conditions in the two cylinder chambers are met.

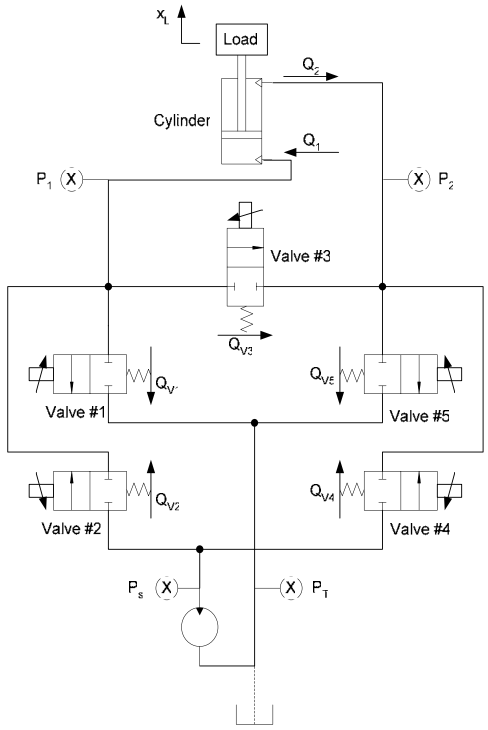


Figure 1. Programmable Valves Configuration.

Rigorously, the meter-in and meter-out flow rates Q_1 and Q_2 are defined by:

$$\begin{aligned} Q_1 &= +Q_{v2} - Q_{v1} - Q_{v3} \\ Q_2 &= -Q_{v3} - Q_{v4} + Q_{v5} \end{aligned} \qquad (2)$$

where Q_{vi}, $i = 1,2,...5$, is the orifice flow through i-th cartridge valve. This is the fundamental difference between the programmable valves and the conventional four-way valves. With a conventional four-way valve, the meter-in and meter-out flows are controlled by a single valve, i.e., a single-input and double-output system. Therefore Q_1 and Q_2 are coupled which results in the inability to independently control the pressures at the two cylinder chambers. If the programmable valves are used to control a cylinder motion, Q_1 and Q_2 are controlled by five independent valves. The input is of five degree-of-freedom and the output has only a dimension of two, the redundancy in control input means the full controllability of Q_1 and Q_2 and tremendous flexibility which would enable energy saving as well as precision motion performance. However, the system requires more complicated controls to fully take advantage of these available hardware flexibility of the proposed programmable valves.

Control of Programmable Valves

An EH system controlled by the programmable valves is essentially a multi-input (five inputs) and dual-objective (precision motion control and energy saving) system. To control such a system is far from trivial. The difficulties come not only from the highly nonlinear hydraulic dynamics, large parameter variations (Watton, 1989), significant uncertain nonlinearities such as external disturbances, flow leakage and seal frictions (Merritt, 1967, Yao et al., 2000), but also from the lack for an accurate mathematical model of the cartridge valves and the coordination of the five cartridge valves (Liu and Yao, 2003).

For the controller design purpose, one needs an accurate yet simple model. Although the cartridge valve has simple structure and very fast dynamic response to neglect the valve dynamics, its static model to describe the valve flow rate as a function of the valve input signal and the pressure drop across the valve is still very complex and not suitable for the controller design purpose (Du, 2002, Johnston et al. 1991, Vaughan et al. 1992, Liu et al. 2002). The lack for the mathematical design model may be solved by one of the following approaches:

1. the experimentally obtained non-linear flow mapping look-up tables,
2. the manufacture supplied flow mapping,
3. the automated on-line modelling of the valve flow mapping.

One of the experimentally obtained flow mappings and the manufacture supplied one are shown in Fig. 2. With the experimentally obtained flow mapping, excellent tracking performance was achieved by Liu and Yao (2003), as shown later by the experimental results. The manufacture supplied flow mapping may introduce a large modelling error due to the fact that cartridge valves are not designed for precise control. Figure 2 shows clearly that the manufacture supplied flow mapping is of significant difference from the experimentally obtained one. The control of the programmable valves with the manufacture supplied flow mapping was solved by Liu and Yao (2004) with guaranteed stability yet degraded tracking performance. The automated on-line modelling of the cartridge valve flow mapping may be the ultimate solution because it eliminates the need for the individual calibration of each valve and the large flow modelling error through on-line adaptation. The approach is being developed.

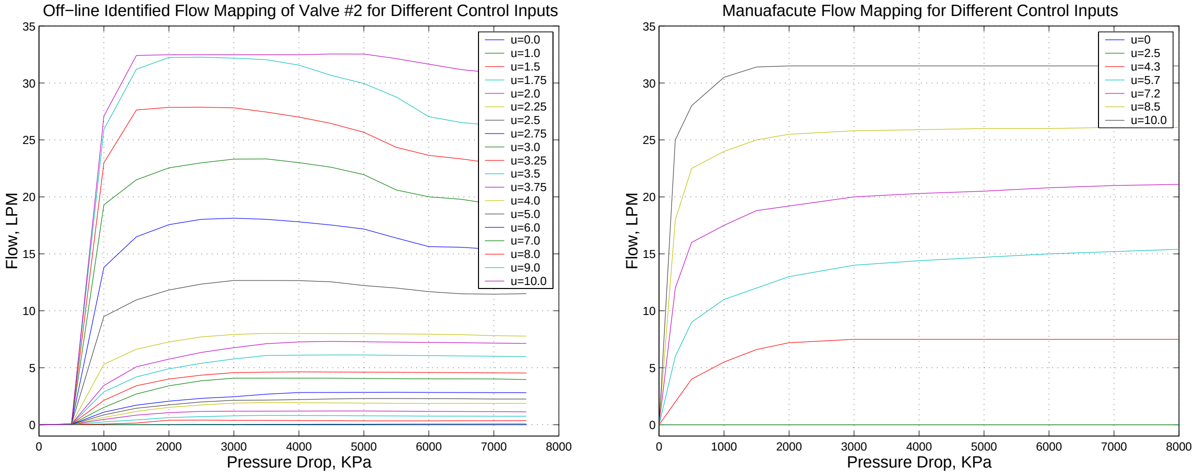


Figure 2. Experimental and Manufacture's Flow Mapping.

The difficulties to coordinately control the five cartridge valves for precision motion control are dealt with through a two-level control system (Liu and Yao, 2002), shown in Fig. 3. The task-level control, also known as the working mode selection, determines how to coordinate the five cartridge valves to enable significant energy saving while without losing the hydraulic circuit controllability for precision motion tracking according to the reference motion trajectory and the current system states. The valve-level control calculates the desired meter-in and meter-out flow commands and distributes the meter-in/out flows into the five cartridge valves based on the selected working mode. The adaptive robust control (ARC) technique, which is a non-linear model based control technique, is applied in the valve-level control to take into account the hydraulic nonlinearities, parametric uncertainties and uncertain nonlinearities (Liu and Yao, 2003).

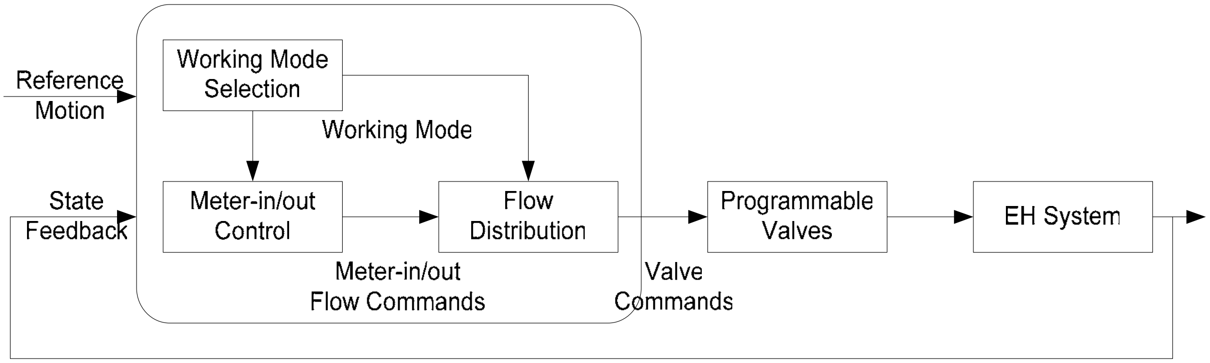
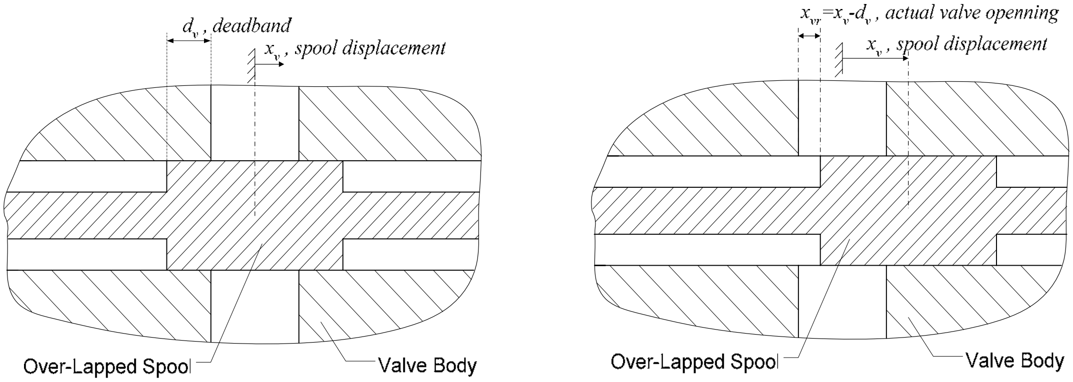


Figure 3. Block Diagram of Programmable Valves Control System.

Programmable Valves: a Solution to Bypass Sandwiched Deadband

Closed-center valves are widely used in industry for position or velocity control. Over-lapped spools are intentionally added in this kind of valves to prevent internal leakage so that the system can hold a position even when the power is off. A side effect of the over-lapped spool is the introduction of the deadband between the spool displacement and the actual valve orifice opening, as shown in Fig. 4. It is obvious that the valve would not open until the spool displacement x_v exceeds the deadband value d_v. It is also obvious that the deadband between the spool displacement and the actual valve orifice opening is sandwiched by two dynamic blocks --- the valve dynamics and the plant dynamics, as shown in Fig. 5.



Spool in Neutral Position

Spool in Positive Displacement

Figure 4. Over-Lapped Spool of Closed-Center Valves.

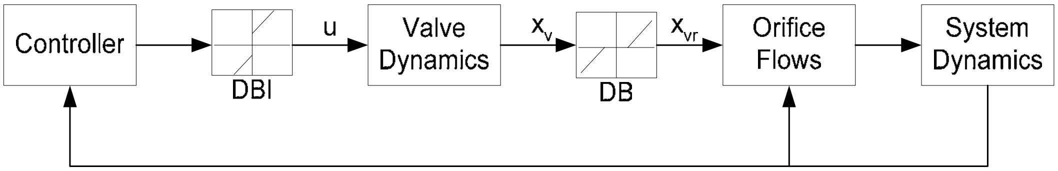


Figure 5. PDC/servo Valve Controlled Hydraulic System.

The sandwiched deadband problem is both theoretically and practically difficult to solve, and degrades the achievable control performance or even destabilizes the closed-loop system if not properly dealt with. A conventional method to solve this problem is the direct deadband compensation, i.e., using an inverse deadband function to cancel or compensate the deadband without considering the effect of the valve dynamics (Fortgang et al. 2002, Bu and Yao, 2000), as illustrated in Fig. 5. This method requires two conditions: a) the deadband property is known or accurately estimated, and b) the valve dynamics is fast enough to be neglected. The first condition may be achieved though off-line system identification (Bu and Yao, 2000) or through on-line parameter adaptation (Tao and Kokotovic, 1996). The second condition usually does not hold unless sacrificing some system performances, i.e., to limit the achievable closed-loop system bandwidth so that the valve dynamics (usually pretty slow for PDC valves) is "faster enough" when compared with the closed-loop bandwidth. Though both the feed-forward controller (Bu and Yao, 2000) and the local high-gain feedback control (Tao and Kokotovic, 1996, Taware et al., 2001, Bu and Yao, 2000) have been proposed to boost the valve dynamics response, in practice, neither method was able to improve the overall control performance significantly due to several implementation constraints as revealed by the experimental results done by Bu and Yao (2000). Namely, the success of using the feed-forward controller (Bu and Yao, 2000) heavily depends on the accuracy of the valve dynamics, while the local high-gain feedback controller (Tao and Kokotovic, 1996, Taware et al., 2001, Bu and Yao, 2000) needs the measurement of the valve spool position, which tends to be too noisy to be of much usefulness, aside from the much increased system cost of having the spool position sensor.

The poppet type cartridge valves, as shown in Fig. 6, also have deadband, but the deadband is due to the fact that the input signal has to be large enough to overcome the pre-load spring force and the static friction, provided that the electrical dynamics of the valve can be neglected. Once the poppet moves, the orifice opens. Therefore, the deadband is of the input deadband type and is of one-directional, which is easy to cancel, as illustrated in Fig. 7. In addition to this benevolent nature of the deadband, the dynamic responses of the cartridge valves are usually much faster than PDC valves due to the simple structure and the much lighter inertia of the poppet compared to the spool of the PDC valve. Neglecting cartridge valve dynamics is thus more reasonable than neglecting PDC valve dynamics in the overall control system design.

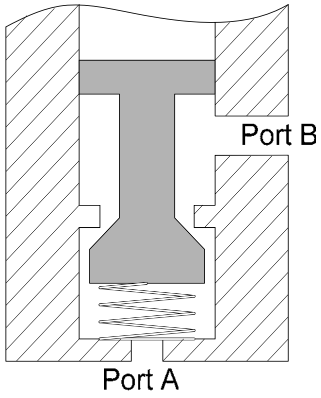


Figure 6. Poppet Type Cartridge Valve.

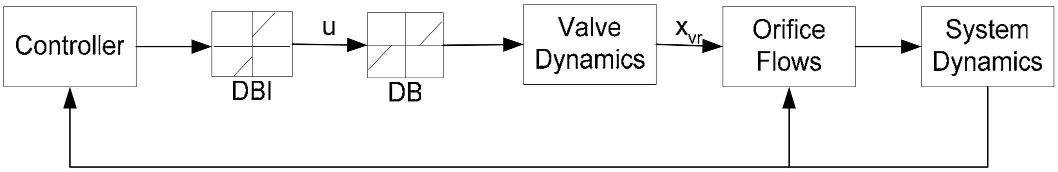


Figure 7. Programmable Valves Controlled Hydraulic System.

Experimental results

The programmable valves (the combination of five proportional poppet type cartridge valves --- *Vikers EPV10-A-8H-12D-U-10*) are used to control the boom motion of a three degree-of-freedom EH robot arm located at Ray W. Herrick Laboratories, Purdue University, to show the effectiveness of the valves and the control system. Two point-to-point reference motion trajectories, shown in Fig. 8, are tested. The fast trajectory has maximal angular acceleration and velocity as $5\ rad/s^2$ and $1\ rad/s$, which are both close to the physical limits of the system; the slow trajectory has maximal angular acceleration and velocity as $0.2\ rad/s^2$ and $0.08\ rad/s$.

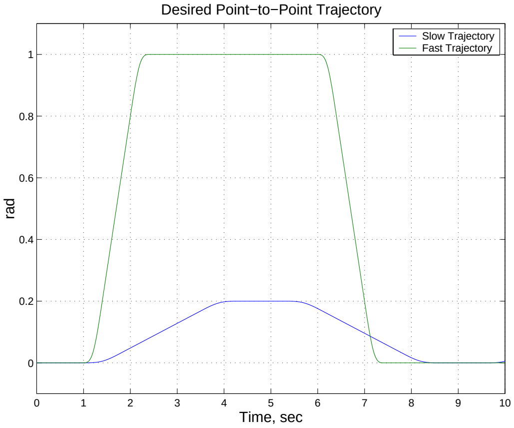


Figure 8. Point-To-Point Reference Motion Trajectories.

The experimental results with and without a $25\ Kg$ load, Fig. 9 and Fig. 10, show that the controller performs well in each case with a maximal error less than $0.02\ rad$. The cylinder pressures in all cases remain very low. The energy usage is calculated as the product of the pump flow rate and the supply pressure. The energy usage is almost zero during the downward motion period, when the regeneration flow is used to activate the motion, as seen between the time of 5-9 seconds.

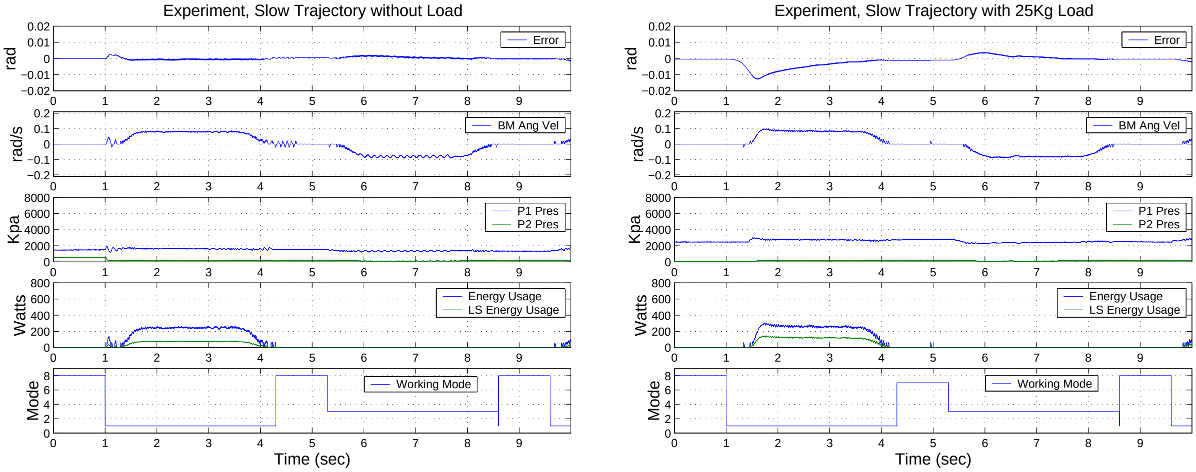
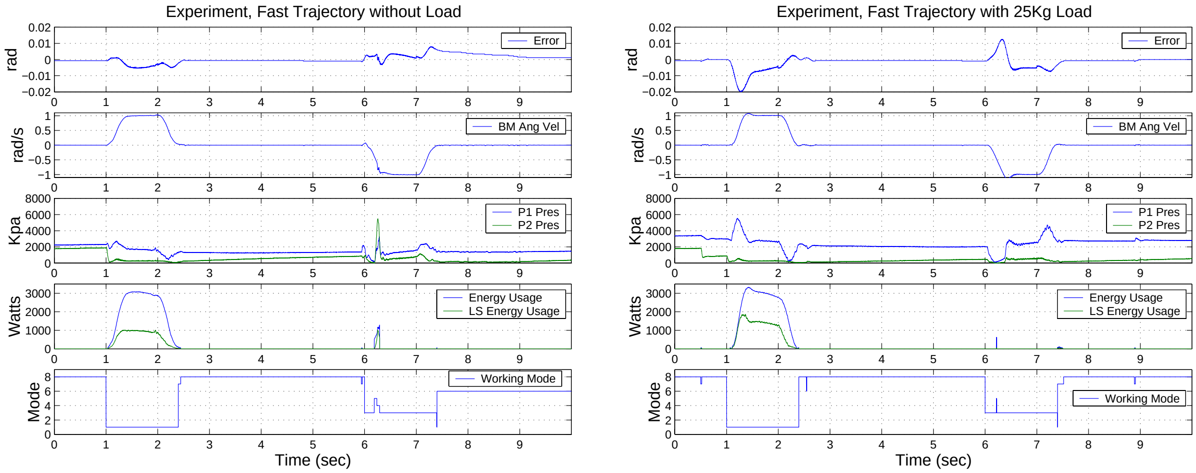


Figure 9. Experiment Results, Slow Trajectory.

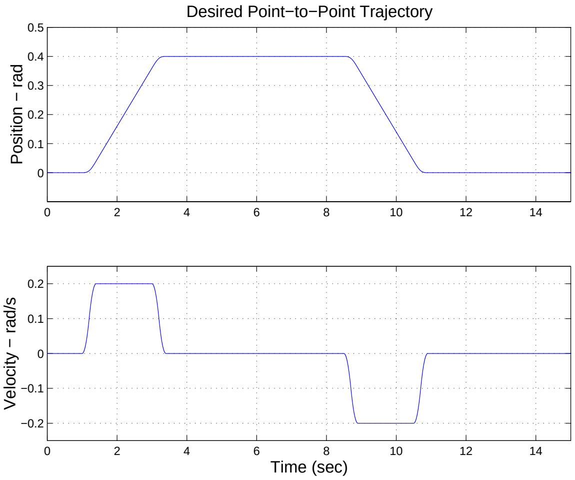
The plots of the energy usage include an additional line representing the potential decrease in energy usage with a load sensing pump. The current set up makes use of a constant pressure supply that is not highly efficient. A load sensing pump that can provide the needed flow at the highest working pressure would significantly reduce the energy usage if used in conjunction with the programmable valve. The plot labeled as 'LS Energy Usage' calculates the anticipated energy usage if a load sensing pump is used. It also assumes that the pump would track the highest working pressure and adds an additional $500\ KPa$ margin of pressure.


Experiment, Fast Trajectory without Load

Experiment, Fast Trajectory with 25Kg Load

Figure 10. Experiment Results, Fast Trajectory.

For comparison, a closed-center four-way PDC valve (*Vikers KBFDG4V-5-2C50N-Z-PE7-H7-10*), a critical center servo valve (*Paker BD760AAAN10*) and the programmable valves are used to control the boom motion to track a point-to-point motion trajectory shown in Fig. 11. The reference trajectory is not as aggressive as the fast trajectory in previous experiments and has longer low speed moving and stationary periods to clearly show the effects of deadband. The experiments are carried out for the system with the PDC valve without/with deadband compensation, the servo valve, and the proposed programmable valves respectively to compare their achievable performances in implementation. The tracking errors are shown in Fig. 12. Not surprisingly, the PDC valve without deadband compensation exhibits the largest tracking error both in the transient and the steady state. The PDC valve's performance is greatly improved by the simple deadband compensation as shown in Fig. 5. Both the servo valve and the proposed programmable valves show excellent tracking performances (noting the smaller scales for the servo and programmable valves in the plot), but the programmable valves have shorter transient periods.


Desired Point−to−Point Trajectory

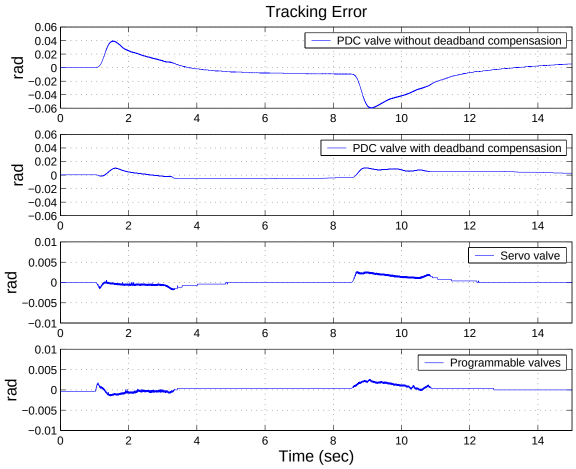

Tracking Error

Figure 11. Desired Point-to-Point Trajectory.

Figure 12. Comparative Tracking Performance.

Conclusion

The proposed programmable valves break the mechanical linkage between the meter-in and meter-out orifices and enable the use of the true cross port regeneration flow. They are able to do precision motion control as well as significant energy saving. They are also a practical solution to bypass the hard-to-deal-with sandwiched deadband which exists in EH systems controlled by conventional closed-center four-way valves. The two-level control system with the ARC technique has been shown to successfully control the system to achieve the dual objectives of precision motion trajectory tracking and significant energy saving. The experimental results show the performance of the programmable valves is as good as, if not better than, the performance of expensive servo valves. The programmable valves are promising alternatives for the conventional four-way valves in precision motion control.

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