Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

ON PRESSURE/FORCE CONTROL OF A 3 DOF WATER HYDRAULIC MANIPULATOR

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ABSTRACT

Force output of a hydraulic cylinder can be controlled by using either load cell or cylinder pressure feedback. Both forms of feedback have good features: load cells usually give more sensitive and accurate response to the external loads while pressure cells respond faster to changes in valve input and are much easier to install. Pressure feedback can easily be used also with rotary actuators but torque sensors are not widely available. In this study, force based motion controller design for 3-DOF water hydraulic manipulator is implemented. The target of this study is to compare the performance of load-cell feedback that is almost ideal feedback for force in terms of high sensitivity and accuracy to more practical and cost affective pressure feedback. Measured results with 3-DOF water hydraulic manipulator are presented in order to verify the findings.

KEY WORDS

Force based motion control, water hydraulics, force control, hydraulic manipulator

INTRODUCTION

Force control applications with hydraulic actuators are most commonly realized with pressure sensors and the force is measured indirectly from the chamber pressure signals. Main reason for this is the price of the pressure sensors compared to the price of the load cells, but load cells are also more difficult to assemble to the mechanical structure of the machine. One problem with both controllers is the disturbances caused by the change of volume flow and flow direction. The most vicious problem in the force control of hydraulic actuators is the seal friction inside the actuator. This leads to different characteristics between pressure signal and force signal based force controllers. Pressure signal based feedback reacts fast to changes on the valve input, but the static accuracy is not very good due to the seal friction. Seal friction is also the reason for the poor sensitivity for external forces. The seal friction can be compensated to some extent with complicated models, but due to the nature of the phenomenon it can never be fully compensated. Force signal based feedback is, on the other hand, faster to react to external forces and the static accuracy is better. Also sensitivity for external forces is higher.

In this study, force based motion control of a 3 DOF hydraulic manipulator is considered. In force based motion control scheme shown in Figure 1, a force controller is an inner loop controller and an upper loop controller is PD-position controller with gravity compensation. With electric robots inner loop force/torque controller is not usually required because motor torque is proportional to input current. In hydraulics, servovalve input is proportional to actuator velocity. Therefore, for hydraulic applications demanding actuator force/torque control capability, inner loop force controller is required. In this paper, force based position control of water hydraulic manipulator is studied under pressure feedback and load cell force feedback. Measured results are presented.

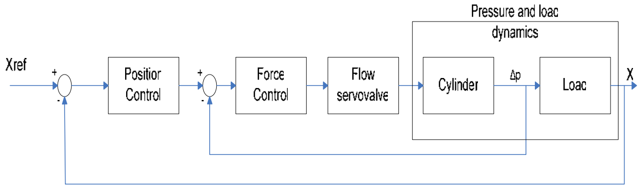

Figure 1. Force based position controller

PERFORMANCE COMPARISON

The performance of the force and pressure controllers were first compared in 1 DOF rotary joint driven by water hydraulic cylinder. Both controllers were simple proportional controllers with the same gain to allow comparison. Size of the cylinder is 32/25-300 mm, the test joint maximum torque is above 1000Nm throughout the motion range, which is 120°. The cylinder is driven by a flow control servovalve.

The properties of both controllers were measured by its frequency response, step response and by a droop test. Frequency response measurement was used to define the bandwidth of two different control systems. The open-loop frequency response measurement of the test bench was first performed. The result from valve input to velocity without contact revealed bandwidth of 11.3Hz. The rest of the measurements were done with the boom in contact with stiff environment so that the reference force to the cylinder was 2500N. Input signal was band-limited white noise (BLWN) with peak amplitude of approximately 500N. Frequency responses were identified based on BLWN input and force output with ETFE (Empirical Transfer Function Estimate)-function of Matlab's Identification toolbox. Figure 2 shows the frequency response of pressure signal feedback with the bandwidth is about 20-21 Hz. Figure 3 indicates that the bandwidth of the pure force signal feedback is about 16-17 Hz.

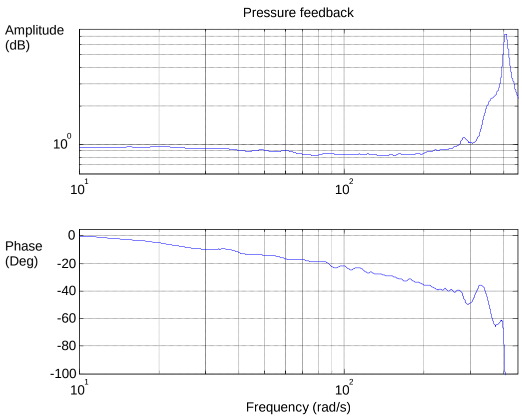

Figure 2. Frequency response of pressure signal feedback

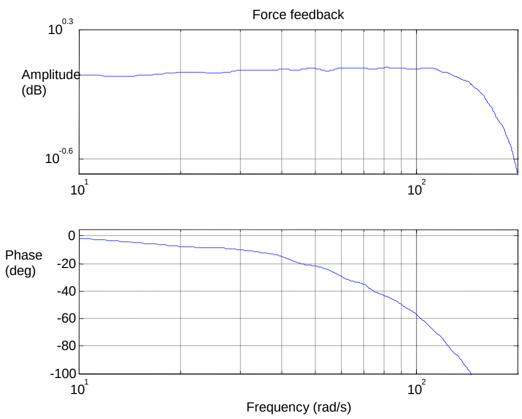

Figure 3. Frequency response of force signal feedback

Step responses were used to verify the results obtained from frequency response measurements. They were also measured when the boom was in contact with the stiff environment. Figure 4 shows the step responses of the force and pressure signal feedbacks. These graphs show that the pressure signal based feedback controller reacts faster to the change in valve input than force signal feedback controller.

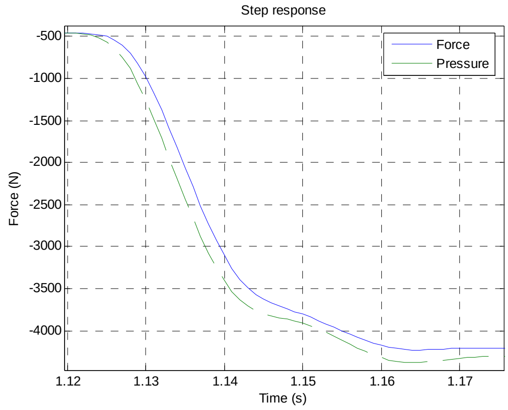

Figure 4. Step responses of force and pressure signal feedbacks

Droop measurements were made to compare sensitivities (backdrivability) between force and pressure signal feedbacks. The measurements were done by slowly moving the boom manually up and down. Ideally the increased cylinder velocity would not increase the motion resistance. From Figure 6 it can be seen that minimum force of about ± 500 Nm is required to move the rotary joint. On the other hand, Figure 5 indicate that with load-cell force feedback and force control, rotary joint responses to external load in fairly linear way without bias force.

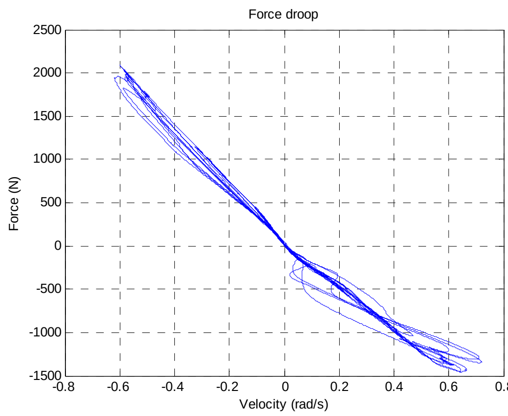

Figure 5. Force signal feedback droop

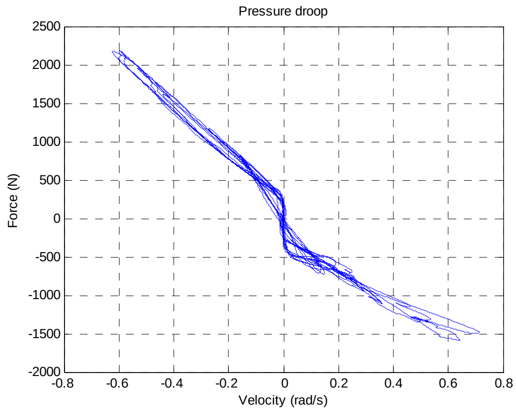

Figure 6. Pressure signal feedback droop

3 DOF MANIPLATOR MEASUREMENTS

Water hydraulic 3 DOF manipulator, shown in Figure 7, was tested with upper loop position and inner loop force or pressure feedback controller. 3 DOF manipulator operates in vertical plane with three actuators. Therefore, two joints are defining the vertical position in XY-plane and the third joint is defining the wrist orientation.

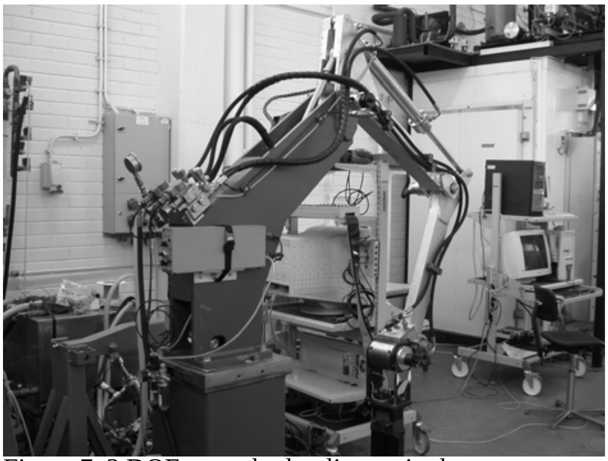

Figure 7. 3 DOF water hydraulic manipulator

Manipulator measurements were carried out under PD-position controller with gravity compensation. The X- and Y-coordinates describes the position of the third joint (wrist) axis. Wrist angle is defined as horizontal angle of the third joint. The schematic of the 3 DOF water hydraulic manipulator is shown in Figure 8.

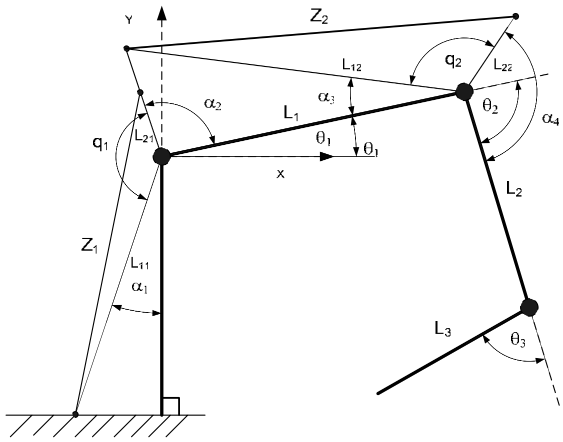

Figure 8. Schematic picture of 3 DOF water hydraulic manipulator

First and second joint are rotary joints driven by water hydraulic cylinders. Both cylinders are equipped with pressure transducers and load-cells installed on cylinder stroke axis. Third joint is vane actuator type and only equipped with pressure transducers. Therefore in both measurements presented, third joint has inner loop pressure feedback controller. Joint angles are measured by pulse encoders. Upper loop position controllers are simple PD-controllers with the same controller gains in both measurements

$$F_R = K_V(\dot{\theta}_R - \dot{\theta}) + K_P(\theta_R - \theta) \qquad (1)$$

Trajectory generator is used to create joint motions between the Cartesian reference position. Inverse kinematics are used for converting Cartesian reference positions to joint angle references. Manipulator was programmed to execute a rectangular box in Cartesian space, shown in Figure 9, while keeping a constant horizontal wrist angle at -90 deg. Next measured results for force based motion controller with inner loop force feedback controller and inner loop pressure feedback controller are presented. Upper loop PD-controller has same gains in both measurements to allow inner loop performance comparison. Inner loop force/pressure controllers are simple proportional controller with about same gains. The gains of the pressure feedback controllers had to be decreased a little bit from values that worked good for force feedback inner loop controller. Although results therefore do not provide perfect comparison between two controllers, it is more important to show a benchmark result of force feedback based controller with quite modest time spend with whole motion controller tuning.

Measured results with inner loop force feedback controller

Inner loop controller in first measurement presented is using force feedback provided by load-cell installed on cylinder rod axis. Figure 9 shows the resulting Cartesian position reference and the calculated Cartesian position (forward kinematics) of the manipulator wrist (third) joint in vertical XY-plane.

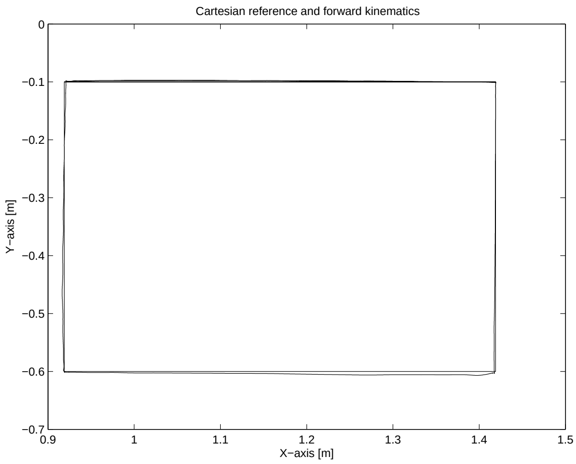

Figure 9. Cartesian reference and position

Cartesian space tracking error versus time is shown in Figure 10.

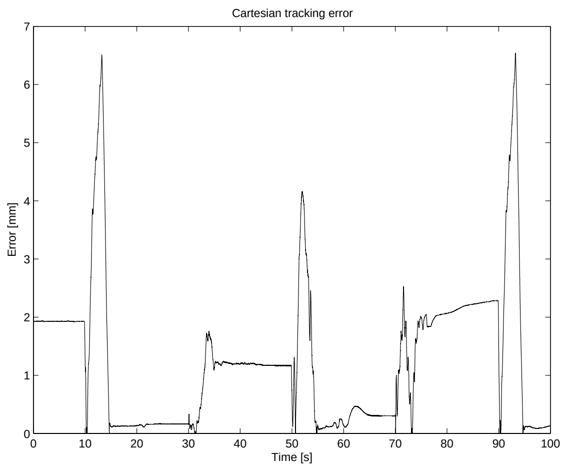

Figure 10. Cartesian tracking error

From Figure 10 it can be seen that static position accuracy is good but dynamic tracking accuracy should be somewhat improved. One reason for poor dynamic tracking accuracy is Cartesian space trajectory generator with trapezoidal velocity profile that results step-like acceleration/deceleration. Also, model-based control was not used in the upper loop controller for linearizing and decoupling of manipulator dynamics.

The measured joint positions and their references are presented in Figure 11.

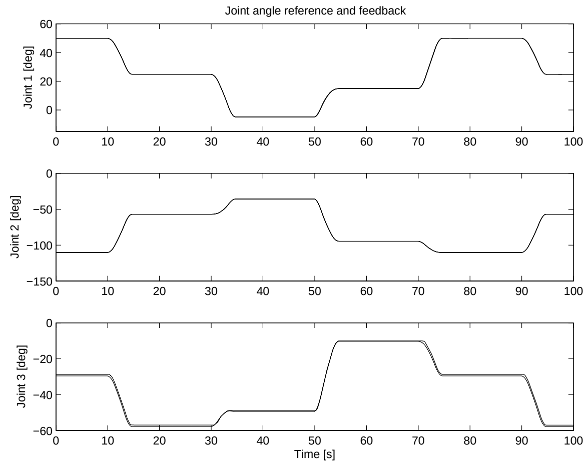

Figure 11. Joint angle references and measured angles

Finally, in Figure 12, resulting force reference and feedback signals are shown.

From Figure 12, it can be seen that force feedback tracks force reference quite well expect that acceleration phase of the motion results large tracking error. This is in part due to step-like acceleration motion profile in Cartesian space.

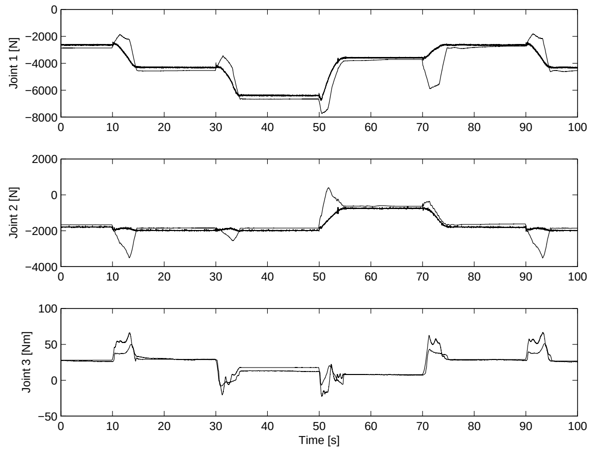

Figure 12. Joint force/torque and references

Measured results with inner loop pressure feedback controller

Second measurement was done by using pressure feedback controller as an inner loop of motion controller. Pressure signal feedback is more challenging control feedback signal than force feedback signal from load cell. This is in part due to direct effect of valve spool position to cylinder chamber pressure. This is because valve spool position is directly proportional to time derivate of pressure. On the other hand, load cell feedback is less sensitive to fast servovalve spool movements. With pressure transducers sensor price has direct effect on sensor signal quality and bandwidth. In this study, medium priced pressure transducers were used and therefore more expensive sensors should have an effect to the results.

In next Figure 13, the result for pressure feedback controller is shown.

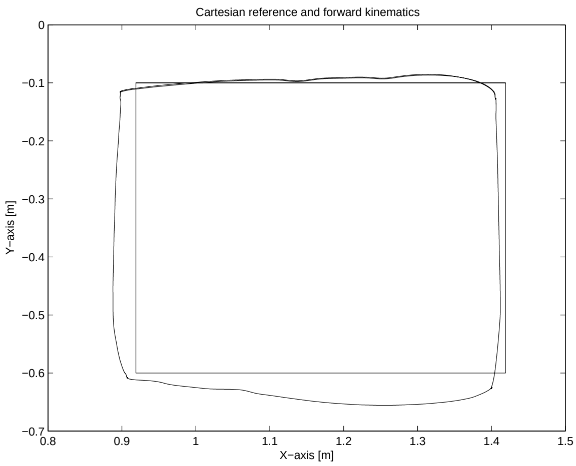

Figure 13. Cartesian reference and position with pure pressure feedback

Cartesian space tracking error versus time is shown in Figure 14.

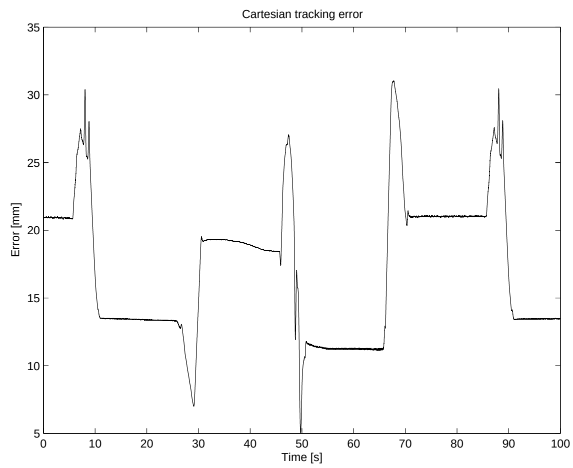

Figure 14. Cartesian tracking error with pure pressure feedback

By comparing Figure 10 and 14 it can be seen that Cartesian space tracking error is about decade bigger than with inner loop force controller. In next Figures 15 and 16 joint angle and force/torque tracking are presented.

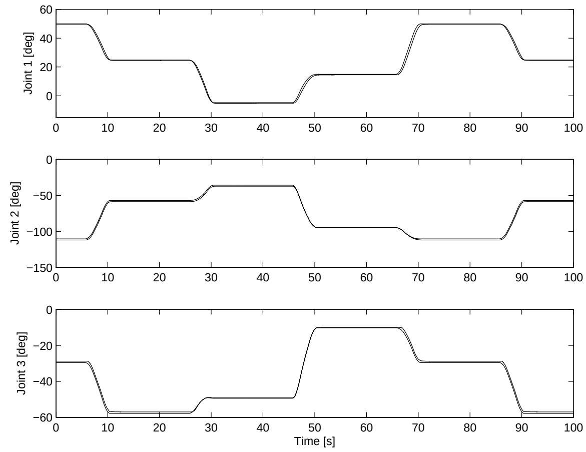

Figure 15. Joint angle references and measured angles with pressure feedback

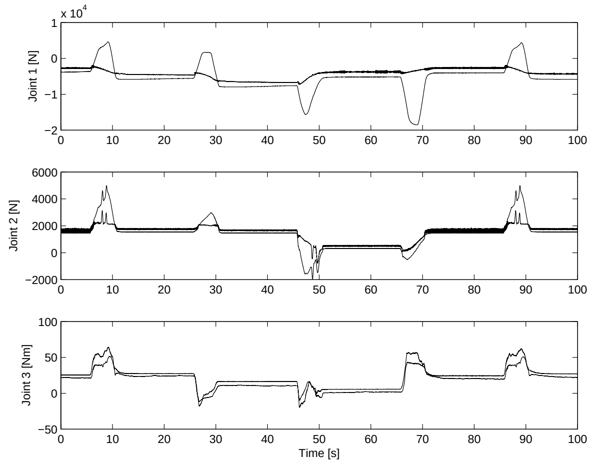

Figure 16. Joint force/torque references and measured with pure pressure feedback

By comparing the results obtained with two different inner loop controllers, it is evident that load cell force feedback controller is outperforming pressure feedback controller. The remarkable thing is that force feedback inner loop controller is quite easy to tune compared to pressure feedback controller. Alleyne [2] has shown the difficulty of tuning hydraulic force controllers mainly from theoretical point of view but theory presented holds for both pressure and force feedback. However, measured results especially with force feedback controller, show that force based motion control of hydraulic joints results quite satisfactory tracking accuracy both in position and force. Obtaining same kind of accuracies with pressure control based motion controller, on the other hand, requires much additional work and possibly model-based seal friction compensation control. The downside of these results is that load cell feedback is feasible only at high-end robotic applications. For hydraulic rotary actuators like vane actuators pressure feedback is only feasible due to lack of torque feedback sensors of reasonable size and weight. As a continuing study, pressure feedback based inner loop controller will be improved and for that force feedback based results serve as a good benchmark.

CONCLUSIONS

In study pressure feedback based force control is compared to force feedback based controller. Measured results with 3 DOF water hydraulic manipulator are presented. Both inner loop controllers are simple proportional controllers with the about same tuning to allow comparison. Pressure sensor signal feedback quality did not allow as high proportional gain as force sensor signal did. Outer loop position controller is PD-controller also with the same tuning in both cases. Results showed that force feedback based motion controller is about decade better in Cartesian space position tracking accuracy as compared to pressure based motion controller. Difference in results can be explained to be mainly due to sensor signal quality and joint friction.

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