THE ROBUST TRAJECTORY CONTROL USING DISTURBANCE OBSERVER
OF A 6-LINK HYDRAULIC MANIPULATOR

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ABSTRACT

In this research work, we are studying the accurate trajectory control at the end of a 6-axes hydraulic manipulator regarding robustness with respect to changes in the system parameters that have unstable characteristics. In particular, interference in the various axes becomes important for improving the accurate trajectory control, and disturbance estimation and compensation by an observer are applied and evaluated by independent servo-system for each joint. As a result, it was verified by experiment that robust, stable accurate trajectory control can always be achieved against fluctuations in the moment of inertia caused by changes in the attitude of the manipulator, and against the nonlinear disturbances, such as axis interference, that are characteristics of a multi-jointed arm.

Key Words

Manipulator, Hydraulic Actuator, Disturbance Estimation and Compensation, Observer, Robust Control

1. Introduction

In a hydraulic servo system, if the system is a type-1 control system, then one of its characteristics is that if an inertial load is driven, then due to the integration property of the actuator, there is no longer any constant deviation (offset). But in a hydraulic servo, the integration properties of the actuator are affected by an added normal position property due to nonlinear characteristics such as the solid friction, the play, or hysteresis of the system, the internal model principle is not satisfied, a constant deviation (offset) arises, and the constant disturbance removal properties are inadequate. This is particularly pronounced when in a state where the loop gain can not be set high. This problem alone can be solved by adding PID control, but planner skill is required for selecting the optimum parameters for such PID controller. With the conventional method by which loop shaping control systems are designed using the frequency response on a Bode diagram or Nyquist diagram, there is also control known as an 1-degree-of-freedom system, and there is a tradeoff between target-value response and stability, with no way to determine gain redundancy or phase redundancy.

A disturbance observer is used for inferring the friction properties of an electric servo. But if the disturbance is
taken to include all deviations from a linear model and all parameter fluctuations, then the use of a disturbance observer makes it possible to compensate for the various nonlinearities characteristic of a hydraulic servo and for the interaction between axes that is characteristic of a manipulator. Superior high-speed responsiveness is also characteristic of a hydraulic servo, so the control signal for it must be obtained in a short time, and control using a disturbance observer has the advantage that the controller can be realized in a form that entails relatively small amount of computation.

The authors of this paper have been engaged in research in high-precision robust control of a hydraulically driven multi-joint manipulator. The problem remaining with hydraulic drive was that it is more difficult to have both stability and high-precision positioning than it is with electric drive. To overcome this problem, we examined disturbance compensation methods using a disturbance observer and studied the possibility of their application. As a result it was confirmed that the control system can be made more rigid without raising the loop gain, and that this is effective against displacement of the center-point of servo-valves and against fluctuations in steady state system parameters, including fluctuations in loop gain and fluctuations in the moment of inertia. It has also been confirmed that this method is robust against nonlinear disturbance inputs such as the mutual interference between axes that is characteristic of a multi-joint arm.

This paper reviews the characteristics of disturbance estimation and compensation and reports on results that experimentally confirm the robustness of disturbance estimation and compensation control against nonlinear inputs and gravity between axes when applied to all six links of a manipulator.

2. Manipulator system

2.1 Problems in a hydraulically driven multi-joint manipulator

A hydraulically driven manipulator has the following problems:

1. The parameters of the system fluctuate depending on changes in the oil temperature, the mixing-in of air bubbles, and fluctuations in the working pressure.

2. A hydraulically driven system is almost always directly driven by a cylinder and is directly affected by the nonlinear disturbance inputs that are characteristic of a multi-joint manipulator.

3. In controlling a multi-joint manipulator of low mechanical rigidity, high-order vibration must be prevented by making the loop gain as low as possible, and it is difficult to also achieve high-precision control.

Here we present results that confirm experimentally that the track precision is improved introducing a relatively simple method by applying a method of disturbance estimation and compensation to a six-links control system, which has dynamic parameter fluctuations, including the above-mentioned axis interference forces. And with disturbance estimation and compensation control, the apparent loop gain is kept high and the system output follows the output of the model even if the actual loop gain is reduced and the stability of the control system is adequately ensured, so this method is effective even in the sense of avoiding high-order vibration such as spill-over.

2.2 Modeling the manipulator control system

In order to construct a disturbance observer, it is necessary not only to make the nominal model of the system with the following assumptions, but also to make an approximation with a second-order system, and confirm beforehand with experiments and step responses by simulations that the output of the system follows the output of the observer model.

1. The servo-valves and servo-amplifiers are assumed as proportional elements.

2. The oil is taken to have no compressivity.

In addition in order to obtain good results with track control it is necessary to have disturbance observers according to the same model for all axes, in order to make the angular velocity deviation equal for all axes.

The valves used for angle control of the joints are nozzle flapper-type servo-valves having a bandwidth of about 120 Hz. Figure 1 shows a block diagram for the spool valve, from deviation error e to load output x.

From Figure 1, the transfer function from the deviation to the output, we obtain

\[
\begin{align*}
\frac{K_p e}{1 + P_l} A \frac{1}{Ms} \frac{v}{1 + s} x
\end{align*}
\]

Figure 2. a block diagram for the spool valve, from error e to load output x
\[
\frac{X(s)}{E(s)} = \frac{C_2}{s^2 + C_1 s + C_2}
\]

where

\[
C_1 = \frac{D + A^2 K_p}{M} \tag{2}
\]

and

\[
C_2 = \frac{A K_p K_e}{M} \tag{3}
\]

Ke: control gain  
Kz : \( \frac{\omega_1}{\omega_z} \)  
A: cross-sectional area of the piston  
M: load inertial  
D: damping constant of the load

In the above equations, for those parameters whose exact value is not known, such as D, Kz, and Ke, are obtained through comparison between the system's step response by experiment and the model's step response by simulation.

3. Disturbance estimation and compensation type robust control

3.1 Disturbance compensation in a multi-joint manipulator

We infer the disturbance from the rotational angle information for each axis of the manipulator, and we consider techniques for compensating for the disturbance. The kinematics of the manipulator are generally described as follows.

\[
\dot{\mathbf{a}} = M(\mathbf{q}) \ddot{\mathbf{q}} + b(\mathbf{q}, \dot{\mathbf{q}}) + g(\mathbf{q}) \tag{4}
\]

where all the nonlinear interference inputs are canceled, and it becomes possible to do motion control by the dynamic properties of the apparent nominal model. In disturbance estimation and compensation by an observer, the parameter fluctuations, including the error according to the degree of approximation of the model and the nonlinear disturbance inputs of the multi-joint arm, which are expressed by equation (6), are all treated as disturbances to an actuator input axis, are calculated within a computer, and this is compensated in each sampling time, so a very robust control system can be realized.

3.2 Disturbance observer

The basic function of an observer is to infer the state variables that cannot be detected from the state variables that are obtained when the needed output variables or state variables cannot be detected. Therefore an observer normally uses a nominal model, so if parameter fluctuations occur in the system, the correct state can no longer be inferred. This is the biggest drawback of an observer. But a disturbance observer treats all the disturbance inputs that cannot be detected as a single state variable, as expressed in equation (5), and conversely by estimation and compensation the system is matched to the dynamic characteristics of the nominal model (model matching). Therefore in some sense it can be said to be a reverse usage from what is normal. Observers include same-dimension observer and minimum-dimension observer. A minimum-dimension observer is for inferring only the state variables that are considered necessary, while a same-dimension observer infers all the state variables handled by the observer, including those that make up the same dynamic characteristics as the system within the observer and cannot be detected. Therefore a same-dimension observer is somewhat more complex than a minimum-dimension observer. The following describes the characteristics of same dimension observer. As stated above, considering the system state variable vector
which includes the disturbance torque superimposed on the inputs, and setting the manipulator system equations of state to

\[
\begin{bmatrix}
\dot{\theta} \\
\theta \\
\tau_d
\end{bmatrix} = \begin{bmatrix}
A & B & 0 \\
0 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\theta \\
\theta \\
\tau_d
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix} u
\]

the same-dimension observer is described as follows.

\[
\begin{align*}
\dot{\hat{\theta}} &= A\hat{\theta} + Bu + K(y - \hat{y}) \\
\hat{y} &= C\hat{\theta}
\end{align*}
\]

where \(\hat{\theta}\) is the state variable within the observer at the inferred value of \(\theta\), \(\hat{y}\) is the observer output, and \(K\) is the observer gain. It is clear from the foregoing that if the system is completely observable, then observation can be done at any estimation speed, but if it is too fast, then noise will have a large effect on the system stability due to the differentiation effect within the observer. Therefore the pole of the observer is set, by trial and error, to the limit value where noise has no effect. If the computer does not have much computation capacity, it is necessary to build a digital observer by digitizing equation (9), but if the sampling period can kept within no more than 1 msec, there is virtually no impediment to inferring \(\tau_d\) from the state differential equations of equation (9). Among the methods for solving equation (9) is the second-order Runge-Kutta method. The inferred value of the disturbance torque calculated in this way can be expressed as follows, given that the nominal model of the system is expressed by equation (1), its parameters are \(C_1\) and \(C_2\), and the observer gain \(K = [k_1, k_2, k_3]^T\).

\[
\begin{align*}
\bar{D}(s) &= \frac{k_3(\dot{s}^2+C_1 s)}{s^3+C_1 s^2+(k_1+C_1 k_2)s+k_3 C_2} \Theta(s) \\
&= \frac{k_3 C_2}{s^3+C_1 s^2+(k_1+C_1 k_2)s+k_3 C_2} U(s)
\end{align*}
\]

where \(\Theta(s)\) and \(U(s)\) are Laplace transforms of the position and the inputs to the system. Figure 2 shows this relationship in block diagram form. \(Q(s)\) represents as follows.

\[
Q(s) = \frac{k_3}{s^3+C_1 s^2+(k_1+C_1 k_2)s+k_3 C_2}
\]

4. Control experiments

4.1 Step response

For all the axes, disturbances were inferred by observers constructed by the same nominal model, and disturbance compensation control was done from axis 1 to axis 6. For lack of space on the page, not all are shown, but for reference the results for axes 2 and 6 only are shown in Figure 3. From these results, it is possible to make the apparent dynamic characteristics of each axis the same by doing disturbance estimation and compensation using the same nominal model.

4.2 Trajectory control experiments

The effectiveness of disturbance observers is confirmed through trajectory control experiments. To obtain good
results in trajectory control, the response angular velocity of each axis should be the same, but disturbance estimation and compensation by the same nominal model is thought to be effective. In the experiments, the origin coordinates of the manipulator are made the center of rotation of axis 1 as shown in Figure 4, its top is in space, instructions are given so that the top will trace out a circular-arc trajectory within a plane tilted at 45 degree, and a comparison is made of the precision of the absolute position when each angular velocity is varied.

Rotary encoder pulses for the joint angles are entered into the computer, and calculation processing is done with a CPU Intel Pentium (120 MHz). The calculation time, including both inverse kinematics calculation and observer calculation, is kept to less than 0.5 [ms]. Figure 5 shows the result of projecting onto three planes the trajectory of the top when it is made to trace out a circular path of radius 17 [cm] at an angular velocity of \( \omega = \pi/3 \) [rad/sec] without robust control. Figure 6 shows the result under the same conditions with robust control. The trajectories shown here were measured with non-contact two-dimensional trajectory measurement sensors.

These results show that due to the influence of gravity and other factors, there are large deviations from the desired trajectory when disturbance estimation and compensation is not carried out, but with disturbance estimation and compensation the precision is greatly improved. But the error is relatively large, reaching a maximum of about 5 [mm], even when disturbance estimation and compensation is carried out. This discrepancy is thought to be because the angular velocity deviation of each axis is not strictly the same.

Figure 4: Manipulator coordinates and trajectory of the top

Figure 5: The trajectory of the top without robust control (\( \pi/3 \) [rad/sec])

Figure 6: The trajectory of the top with robust control (\( \pi/3 \) [rad/sec])

4.3 Experiments combining estimated disturbance compensation with other compensation methods

In a preliminary stage to doing compensation by an observer, PI compensation elements were added as in Figure 7. The results of the trajectory control experiments
are shown in Figure 8; the precision error is no greater than 1 [mm]. This is considered to be because when a PI compensator is inserted in series in a control system with disturbance estimation and compensation by a type-1 model, which becomes an ideal type-1 system, the system becomes an apparent type-2 system, and velocity deviations are mostly eliminated. These results show that if the desired trajectory precision is not obtained even when disturbance estimation and compensation is applied, it is effective to use it together with a traditional compensator, such as PI compensation.

5. Conclusions

As discussed above, disturbance estimation and compensation makes it possible to infer disturbances by relatively simple computation, and by compensating for them one can achieve the apparent dynamic characteristics of the nominal model. The results obtained by the authors in their research thus far as applied to trajectory control are summarized as follows.

(1) A robust control system can always be built, because even if the parameters of a control system change nonlinearily, their effect can be inferred as a disturbance with respect to the nominal model and corrected for. And because the apparent loop gain is kept high, robust stability can be separately set and maintained by lowering the actual loop gain.

(2) By applying to each of the six axes of a manipulator the robust control obtained with disturbance observers based on the same model, the velocity deviation of the joint axes is made roughly equal, and the trajectory precision is greatly improved.

(3) Because the models used in experiments thus far are basically type-1 models that produce velocity deviation, the desired trajectory precision is sometimes unobtainable even if disturbance estimation and compensation by the same model is applied to each axis. In this case, it has been experimentally verified, the trajectory precision can be improved by combining PI compensation with disturbance estimation and compensation. Disturbance estimation and compensation can be applied not just to hydraulically driven manipulators but to all servo systems, and it is expected to find wider applications in the future. And because the computation it requires is relatively simple, it can be easily constructed with analog circuits alone.

References