CVT Servo-Pump Flow Control

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A continuously variable transmission (CVT) is controlled by a hydraulic system. The standard configuration uses a valve to set the necessary pressure. A pump connected to the engine generates the necessary flow. In order to improve on the current method, a servo-pump system can be used to control the CVT. The shifting pump is used to set the ratio while the clamping pump controls the secondary pressure. As knowledge of the flow is important in setting both the primary and secondary pressures, it is justified to control the flow. This paper discusses the servo-pump model and the state-feedback of the servo-pump flow control and presents a number of results.

Key Words: CVT, servo-pump, control, state-feedback, decoupling

1. Introduction

The continuously variable transmission (CVT) market is continuously increasing. The additional degree-of-freedom provided by this transmission allows for an optimal operation of the power train by controlling the engine at its line of best efficiency.

The CVT variator has two pulleys. Each pulley is composed of one fixed conical sheave and a second conical sheave movable in its axial direction (Fig. 1). The main hydraulic pressure is applied to the secondary pulley to over clamp the belt to avoid slip and guaranty the power transmission. The transmission speed ratio is controlled by displacing fluid from the primary pulley to the secondary pulley or vice versa.

In the conventional hydraulic system, a shift control valve and a relief valve set the primary and secondary pressure respectively. The hydraulic pump is connected to the engine. This pump is always over designed to ensure sufficient pressure under all conditions. To avoid these disadvantages, a system using servo-pump can be used as shown in Fig. 1.

This configuration divides the control of the CVT into a clamping and shifting force. The clamping pump provides hydraulic pressure to both the primary and secondary pistons to prevent any slip of the belt. The function of the shift pump is to provide control of the CVT ratio by regulating the differential pressure between the secondary and primary pistons. Bradley1 and Shastri2 discuss the performance of this new hydraulic system and also show a better efficiency compared with the standard system. The servo-pump system is working on demand: only when flow is needed, the servo-pumps are asking to delivery the necessary flow. In steady-state and if no leakages are considered, the servo-pumps do not rotate.

2. Servo-Pump Model

Three main elements constitute the servo-pump: a servoamplifier, a motor and a pump. For this application the servoamplifier is a Maxon DE S50/5, the motor a Maxon motor type EC60 and the pump is a Marzocchi pump 0.88 cc/rev.

An input voltage $V_{\text{sw}}$ to the servoamplifier sets the desired speed of the motor. The servoamplifier generates
the voltages and controls the motor speed. The motor drives the pump and a flow is generated in the hydraulic circuit. The pressure generates a torque on the motor that the motor will need to compensate by providing the desired speed. To simplify, it is justified to say that the flow $Q$ is proportional to the motor speed.

$$Q = D_v \cdot \omega \cdot \eta_v .$$  \hspace{1cm} (1)

Where $D_v$ is the volumetric displacement of the pump, $\omega$ the rotation speed and $\eta_v$ the volumetric efficiency.

The rotation speed is defined by the voltage $V_{set}$ and controlled by the servoamplifier. The amplifier is a black-box and it was found that the rotation speed of the motor can be described by a second order function.

$$\omega(s) = \frac{K}{a \cdot s^2 + b \cdot s + 1} \cdot V_{set} .$$  \hspace{1cm} (2)

By introducing eq. (2) into eq. (1), the flow given by the servo-pump becomes:

$$Q = \frac{D_v \cdot \eta_v \cdot K}{a \cdot s^2 + b \cdot s + 1} \cdot V_{set} = \frac{G}{a \cdot s^2 + b \cdot s + 1} \cdot V_{set} .$$  \hspace{1cm} (3)

and the state space formulation:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{1}{a} - \frac{b}{a} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{a_v} & \frac{b_v}{a_v} \end{bmatrix} \cdot x + \begin{bmatrix} 0 \\ G \cdot \frac{G_v}{a_v} \end{bmatrix} \cdot u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \cdot x$$

where the state vector $x = [Q \ \dot{Q}]^T$, the input vector $u = V_{set}$ and the output vector $y = Q$.

Now lets consider the complete hydraulic system without the variator. The primary flow $Q_p$ depends only on the input voltage $V_{set, p}$. The secondary flow $Q_s$ is the subtraction of the flow $Q_{op}$ given by the clamping force and the flow $Q_p$. Then the MIMO system in state space formulation becomes:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{1}{a} - \frac{b}{a} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{a_v} & \frac{b_v}{a_v} \end{bmatrix} \cdot x + \begin{bmatrix} 0 \\ 0 \\ G \cdot \frac{G_v}{a_v} \end{bmatrix} \cdot u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \end{bmatrix} \cdot x$$

with

$$x = \begin{bmatrix} Q_p & \dot{Q}_p & Q_{op} & \dot{Q}_{op} \end{bmatrix}^T$$

$$u = \begin{bmatrix} V_{set,p} & V_{set,s} \end{bmatrix}^T$$

$$y = \begin{bmatrix} Q_p \ Q_s \end{bmatrix}^T$$

The servo-pump system is a linear and MIMO system.

If the flow $Q_{op}$ is considered constant, a variation of the input voltage of the shifting pump (variation of the motor speed) $V_{set, p}$ influences not only the primary flow $Q_p$ but also the secondary flow $Q_s$.

By considering the flow $Q_s$ constant, a variation of the input voltage of the clamping pump $V_{set, s}$ influences the secondary flow $Q_{op}$, but does not influence the primary flow $Q_p$.

3. Actuator Controller Choice

The motor can be used in either current control mode (torque control) or in speed control mode. The flow is directly proportional to the rotation speed; therefore the motor is more appropriate in speed control mode.

At first, a PID controller is considered for controlling the flow $Q_p$ and $Q_s$. The poles of the closed-loop define the dynamics of the controller. In this case, the closes-loop poles contain the poles of the servo-pump system and this defines some limitations on the dynamics.

Secondly, a controller using the state-feedback pole placement is considered. The power of the pole placement is that the designer defines the poles of the closed-loop. The internal dynamics loop is not directly taken into account and a controller with a faster response than a PID controller can be designed. The state-feedback method is choosing instead of a PID.

4. State-Feedback

Figure 2 shows a regulator system using state-feedback and an observer. The internal loop controls the internal states so as to always keep them at zero. The external loop controls the output of the plant for a regulation problem such as we have with the control flow of the servo-pump.

The inner loop needs the knowledge of to the system states. As the states cannot be measured, an observer is needed. The observer is basically the model of the plant given by eq. (5) with some extension.

![Fig. 2 Regulation system using state-feedback and observer](image-url)
For the CVT control, the actuator dynamic should be fast enough so as to be neglected. The position of the poles was done through a series of tests on the test rig until fast enough dynamics were reached.

5. Results

Figure 3 shows the responses of the flow control. In the upper right plot, the primary flow demand is maintained constant at zero while a step response is applied on the secondary flow. The lower right plot represents the velocity of the servo-pump. In the upper right plot the secondary flow is constant and a step response is applied on the primary flow. The lower right plot shows the rotation speed of the servo-pump. During the increasing of the primary flow demand, the clamping pump increases the speed to maintain the secondary flow constant. The plots show that the controller is stable and that the MIMO system is decoupled. Also, the response is fast enough to neglect the dynamics of the actuators.

6. Conclusion

This paper has discussed the flow control of the servo-pump hydraulic system used to control the ratio and the clamping force of a CVT. It was shown that the state-feedback is a simple but powerful method for solving the regulation problem. The poles of the closed-loop system can be placed in arbitrary desired locations using a constant linear combination of the state variables. The state and the output cannot be measured; therefore an observer is used to estimate them.

The designed controller is stable and decouples the MIMO system. Also, the bandwidth was increased so as to neglect the dynamics.
References

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