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An Active Disturbance Rejection Control Solution for Electro-Hydraulic Servo Systems

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AN ACTIVE DISTURBANCE REJECTION CONTROL SOLUTION FOR ELECTRO-HYDRAULIC SERVO SYSTEMS

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ABSTRACT

The intriguing history of disturbance cancellation control is reviewed in this thesis first, which demonstrates that this unique control concept is both reasonable and practical. One novel form of disturbance cancellation, ADRC (Active Disturbance Rejection Control), attracts much attention because of its good disturbance rejection ability and simplicity in implementation. Hydraulic systems tend to have many disturbances and model uncertainties, giving us a great motivation to find out a good control method. In this thesis, electro-hydraulic servo control problem is reformulated to focus on the core problem of disturbance rejection. An ADRC solution is developed and evaluated against the industry standard solution, with promising results.

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CHAPTER I

INTRODUCTION

Control engineering plays a very important role in our lives. Almost every single machine has a control system to regulate its behaviors. From aircrafts, automobiles and cranes to air-conditioners, robots and even electronic chips, control is closely connected to the technological development that brings comfort to mankind. For example, a good control system keeps the elevators moving quickly and smoothly even when the load changes within a big range.

Control as it’s commonly defined in current textbooks is mostly limited to feedback systems. In this chapter, a different view of control is discussed in section 1.1. Then the motivation for seeking advanced control methods in electro-hydraulic servo systems is discussed in section 1.2.

1.1 Background

Long before control theory was established, feedback control was used in many mechanical systems. The first application can be traced to the period 300 to 1 BCE when a float regulator was implemented in the water clock of Ktesibios. Perhaps the most famous feedback control device is James Watt's flyball governor. Watt used the flyball governor to control the speed of steam engine by adjusting the steam valve and therefore the amount of steam going into the engine, in response to the deviation of the engine speed from the desired one [1].

These old feedback control systems are mostly pure mechanical devices built based on sheer intuition of their inventors long before any systematic understanding or theory was established. James Maxwell performed the first mathematical analysis of feedback control in 1868, followed by the investigations from other mathematicians over several decades. Classical control theory, as we know today, originated in the Bode and Nyquist's analysis of the performance of feedback amplifiers in frequency domain during 1930s and has since become the standard bearer [1].

Academically speaking, the history of control theory is a history of the study on feedback. In reality, however, there is an alternative, one that is based not on feedback, but on disturbance cancellation. It is recorded that, in 2634 BCE China, the south-pointing chariot was invented in which the disturbance acting on the direction of the chariot is measured and cancelled, thus making the puppet on the chariot always point to the same direction it started with [2]. Obviously, this control function is not based on the conventional notion of feedback and there is no set-point, nor the measurement of the output, which is the direction pointed by the puppet. This form of control is much earlier than the first application of feedback control but received little attention throughout the history of control.

The key in disturbance cancellation control is that the information of disturbances should be obtained by measurement or estimation. Once this information is obtained, it can be used to cancel the effect of disturbances. Since there are plenty of control systems, such as in the hydraulic servo systems as shown later in the thesis, where disturbance rejection is the most important quality, the disturbance cancellation methodology should not be overlooked.

1.2 Motivation

Hydraulics has an eight thousand years of history. Early uses of water power can be traced to Mesopotamia and ancient Egypt. Irrigation has been used since the 6th millennium BCE and water clocks had been used since the early 2nd millennium BCE. In 1619 Benedetto Castelli, a student of Galileo Galilei, published the book "On the Measurement of Running Waters", which can be regarded as one of the foundations of modern hydrodynamics [3].

Hydraulic systems are now widely used in every aspect of our life, such as hydraulic punching, pressing, bending and lifting in machinery manufacture. Hydraulic systems have great advantages such as high power/mass ratio, fast response, high stiffness and high load capability. However, hydraulic systems are highly nonlinear and have many dynamic uncertainties which are consequences of physical characteristics, disturbances and load variations [4].

In industry, PID (Proportional-Integral-Derivative) is commonly used in electro-hydraulic servo control systems. In a PID feedback control loop, adjustment is made only after the disturbance goes into the system and causes the tracking error to occur, often wasting energy in the process. Also, PID often has poor disturbance rejection and uncertainty toleration. Because of the importance of hydraulic systems and the difficulties in control design, there is a great incentive to explore novel control methods to obtain a better performance in electro-hydraulic servo control systems.

1.3 Thesis Organization

This thesis is organized as follows. Literature review on electro-hydraulic servo control and the history of disturbance cancellation control are introduced in Chapter II. The history of disturbance cancellation includes where this method came from, how it has been developed and what is new in recent years. The plant model of electro-hydraulic servo control system is identified and reformulated and nonlinear state space equations are given in Chapter III. In Chapter IV, the control design is described. In Chapter V, simulation results are provided and analyzed. Conclusions and future works are given in Chapter VI.

CHAPTER II

LITERATURE REVIEW

In this chapter, literature review on electro-hydraulic servo control is provided in section 2.1. Then the history of disturbance cancellation, its worldwide expansion and its current development are discussed in section 2.2. A summary is made in section 2.3.

2.1 Electro-Hydraulic Servo

Much research has been done in controlling electro-hydraulic servo systems using various control methods. They could be divided into three paradigms, the industry paradigm, the model paradigm and the disturbance rejection paradigm [5].

The typical control method from the industry paradigm is PID, which must be tuned in each system, often in a tedious process. Moreover, changes in the system dynamics commonly require the PID controller to be retuned in order to obtain a good performance. In addition, PID usually has a poor disturbance rejection. Even so, PID is still dominant technology in industry partially because it does not require the plant model.

Fuzzy PID, the combination of the traditional PID controller and fuzzy logic, can be made to adaptively tune the gain parameters k_p, k_i and k_d according to the error and change in error [4]. Fuzzy PID can tune its parameters by itself, but it is still PID and may not handle the nonlinear and time-varying dynamics very well. When disturbance occurs, it tunes the values of the parameters of PID step by step and finally finds out a solution. But, during this progress, significant amount of power and energy could be lost. There is also work done on combination of fuzzy logic and PID controller implemented in electro-hydraulic position control system [6]. The system is switched to use fuzzy controller or PID controller, depending on the range of the error.

In the model paradigm, the design of control algorithm is based on the plant model that is assumed given. State feedback, feedback linearization, H_∞ control and sliding mode control can be included in this paradigm. Feedback linearization has been used in electro-hydraulic position control system [7, 8], where the plant is linearized by using feedback loop based on the knowledge of system model. Although this control method is very straightforward, it cannot handle unexpected disturbances and uncertainties of the electro-hydraulic systems very well. Another disadvantage of feedback linearization is that system model must be accurate, otherwise linearization cannot be accomplished.

Because of the poor disturbance rejection ability of feedback linearization, H_∞ control method has also been investigated as an alternative. But its use in industry has been very limited because of, among other things, its complexity in implementation, its assumption on having a rather accurate model, and its limited range of accommodation of model uncertainty [9-11].

Similar arguments can be made with sliding mode controller. In sliding mode control, one has to find two functions to satisfy the Lyapunov stability conditions based on the plant model, and this is quite complicated, especially for high-order nonlinear electro-hydraulic systems [12-14]. However, these control methods from the model paradigm can easily outperform the PID controller from industry paradigm, if the plant model is given.

The disturbance rejection paradigm has its focus on the problem of cancelling the disturbance before it significantly affects the output. Critical to its success is the disturbance information, which is obtained using various estimation methods such as the UIO (Unknown Input Observer), the DOB (Disturbance Observer), the POB (Perturbation Observer) and the ESO (Extend State Observer). For UIO and DOB, a nominal model of the plant is needed based on which the external disturbance is estimated. When implemented in electro-hydraulic servo systems, they show some tolerance to model uncertainties and are able to estimate the external disturbances [15, 16]. POB is almost same as DOB, but presented in discrete form [17]. In ESO, the total effect of the external disturbances and internal uncertainties is estimated and then cancelled in the ADRC framework, which is shown to have great tolerance of plant uncertainty and excellent disturbance rejection ability [18].

Generally speaking, PID used in its various modifications does not have good disturbance rejection and plant uncertainties tolerance. Small changes in the plant require operators to retune the controller and much energy could be wasted in the process. With the model based paradigm, the biggest problem is that, with so much uncertainty, especially in the high-order nonlinear system, the controller is not up to the task.

Hence, a better solution for electro-hydraulic servo problem should be sought in the disturbance rejection paradigm. Before this, the history of disturbance cancellation will be reviewed. It should be made clear where this idea came from, how it was developed and what the current situation is.

2.2 The History of Disturbance Cancellation

Nowadays, control system is everywhere and it seems no stone has been unturned in search of better designs. There is one class of solutions, however, known as disturbance cancellation, which has been somehow ignored in the textbooks, but quietly blossomed in many different forms in practice. The history of this development is outlined below.

The earliest device of disturbance cancellation could be traced to the famous Chinese invention of south-pointing chariot [19]. The south-pointing chariot first appeared in legends, according to which the Yellow Emperor, in 2634 BC, was in a war against Chi You, which had lasted for years. At the time Chi You was going to fail, there came a thick fog and Yellow Emperor's troop lost their direction. Yellow Emperor then invented the south-pointing chariot and finally defeated Chi You.

The first recorded south-pointing chariot was attributed to Ma Jun from the Kingdom of Wei, in 235 AD during Three Kingdoms [20]. Later, Zu Chongzhi (478 AD), Yan Su (1027 AD) and Wu Deren (1107 AD) reinvented the south-pointing chariot several times [20]. The History of the Song Dynasty, or *Sung Shi*, has detailed records of Yan Su and Wu Deren’s south-pointing chariot, the former is depicted in Figure 2.1[2]. Gear B rotates with the rotation of wheel A, which makes gear D rotate with a speed proportional to A’s speed. When the chariot is moving forward, gear E is not connected to gear D; when the chariot is tuning left, gear E will engage gear D and its rotation will exactly cancel out the angle the chariot turns, making the wooden image of a immortal, which is connected to gear E and stands on top of the chariot, keep pointing to the same direction, south, as it started with [2].

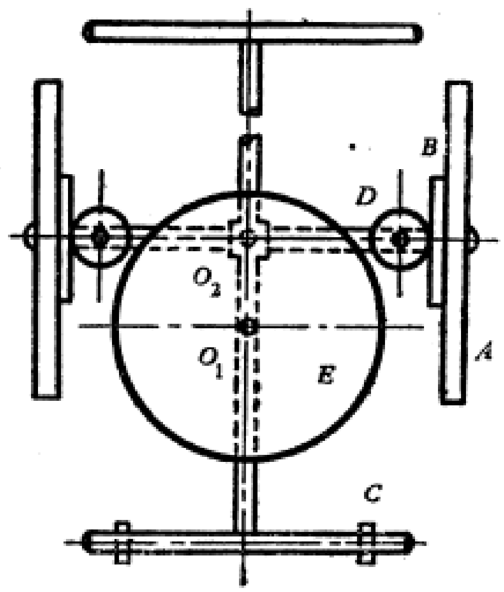

Figure 2.1 Yan Su’s south-pointing chariot [2]

Figure 2.2 Picture of south-pointing model

Figure 2.2 is a picture of south-pointing chariot model. Note that in this control system, the goal is to make immortal on top of the chariot always points to a certain direction (south), and this can be seen as the set point. But this goal is achieved without the feedback of actual direction the immortal points to. Instead, a disturbance is measured and this information is used to make the pointing device turn, cancelling the disturbance effect.

A similar concept appeared in Western literature over a thousand years later. Jean-Victor Poncelet, a French army officer and physicist, proposed a new form of engine governor which was based on the use of disturbance cancellation in 1829. He tried to measure the load disturbance on the engine by a spring coupling and adjust the steam valve accordingly to compensate for it [21], *before* the engine speed changes. Just like the south point chariot, his design doesn't require the measurement of the actual engine speed, as shown in Figure 2.3. In this system, the load change is the disturbance that tends to cause speed change. The torque from prime mover to load passes through a flexible spring coupling. The load change creates a twist in the coupling, which reflects the disturbance torque, and it then passes through the meshed gears to cause the displacement of Gear 2, which changes the throttle valve [22] and regulate the steam flow to cancel the load disturbance.

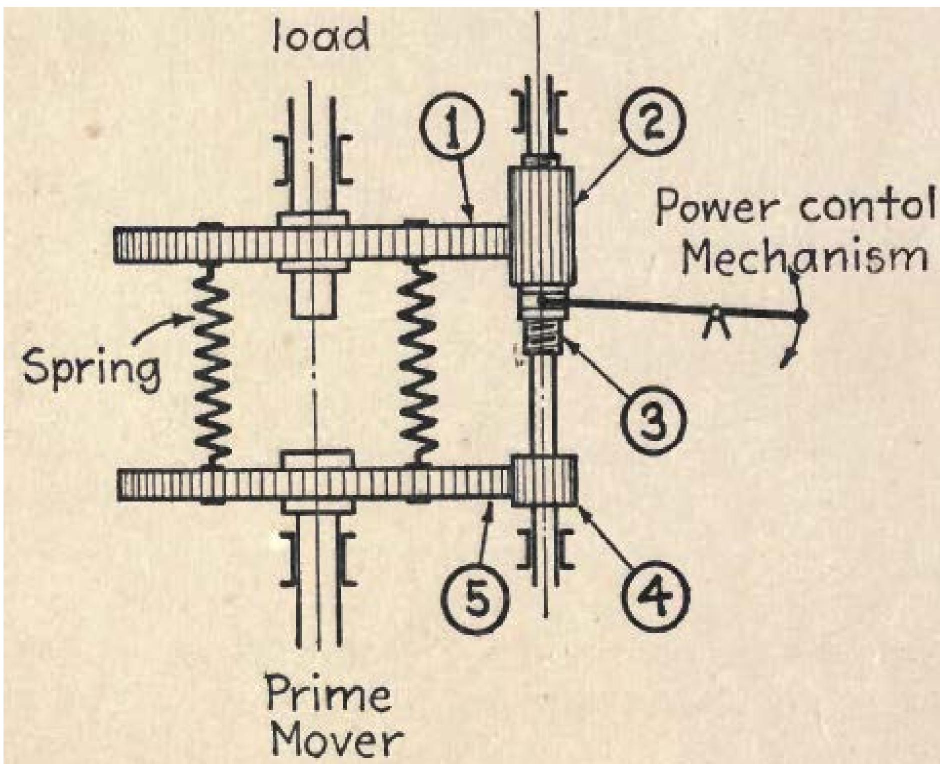

Figure 2.3 Poncelet’s load-sensing governor [22]

In other words, in Poncelet’s governor, the load disturbance is measured instantaneously, which makes the governor act immediately by adjusting the throttle valve (control signal). But Poncelet’s invention was not successfully implemented because of the stability issues such as vibrations due to flexible couplings and sudden load changes. The idea of disturbance cancellation, however, lived on.

It is reported in [23] that disturbance cancellation was applied in Chikolev Vladimir Nikolaevich's "differential" arc lamp. From 1860s to 1870s, the spread of electric light arc lamp was limited by its weaknesses such as the complexity of the design, the inability to include multiple bulbs in one chain, the need for relatively high current for lights, etc. In 1877, Chikolev developed the first differential arc lamp, which solved the problem completely. The regulator of the arc lamp uses both the idea of disturbance cancellation and the feedback amplifier and this might be the first attempt on the combination of disturbance cancellation and feedback.

Later in 1939, the theory of invariance was developed by G. B. Shchipanov, in which Soviet engineers showed great interest. The theory of invariance is to find out how to make an output (or outputs) of a system unaffected by one or more of the inputs. This theory of invariance is trying to solve the essential problem in a control system, the disturbance rejection problem. The conditions of invariance are given by Shchipanov. It is impossible to realize absolute invariance only by using feedback, unless infinite gain is used, which is not realizable in practical control systems. It is said that both feedforward and feedback should be applied to meet the conditions and achieve absolute invariance of a controlled variable. In feedforward, input disturbance is cancelled before it goes into the system in order to make the output invariant to input disturbance [24].

After Shchipanov's theory of invariance was proposed, many Soviet scholars continue to make contributions in the development of disturbance cancellation, particularlyA. G. Ivakhnenko, B. N. Petrov and V. S. Kulebakin. A. G. Ivahnenko showed the importance of disturbance feedforward, which is different from output feedback. He pointed out that feedforward and feedback are ‘orthogonal’. They have different effects in a system separately. In particular the power consumption of a system with feedforward should be much less than the system with only feedback. The greater the accuracy of the feedforward, the less work left to the feedback and less power consumption [25].

Another Soviet scholar, B. N. Petrov, made the following statement: in a dynamic system there must be at least two channels for propagation of influences between the point of application of the external effect and the point of measurement of magnitude. This is later known as the principle of dual channels. It suggests that the controller must act on the disturbances, not just react to its effect on the system performance [26].

Finally, A. S. Kulebakin insists that disturbance compensation based on the theory of invariance deserves more attention among many advanced control methods [27]. That is, disturbance rejection is very important in a control design and feedback alone is not enough. In this paper, Kulebakin also demonstrates the practicality of invariance principle. As combined control system based on dual channel principle was taking roots in Soviet Union, the problem of disturbances cancellation was also considered by engineers in United States.

Elmer Sperry, who developed the first PID-type controller in 1911, invented devices for measuring of and compensating for disturbances like wind, wave, etc. in automatic ship steering system [28]. Figure 2.3 is a simple illustration of a gyrostabilizer used to reducing ship from rocking back and forth along big waves: one the left is the normal condition with no waves and on the right is when the ship (platform) is tilted by the waves. As indicated on the right in Figure 2.4, the gyro wheel will tilt to an angle proportional to the tilt of the ship, which produces the countering force on the platform [29]. Based on this natural phenomenon, Elmer Sperry invented a gyrostabilizer which is used to automatically adjust the gyro wheel inclination by a motor according to the tilt of the ship (Figure 2.5). When the ship rolls, the control gyro will tilt and one of the contacts will be closed. Then the motor will be energized in the proper direction, which adjusts the inclination of the axis of the gyro wheel accordingly [30].

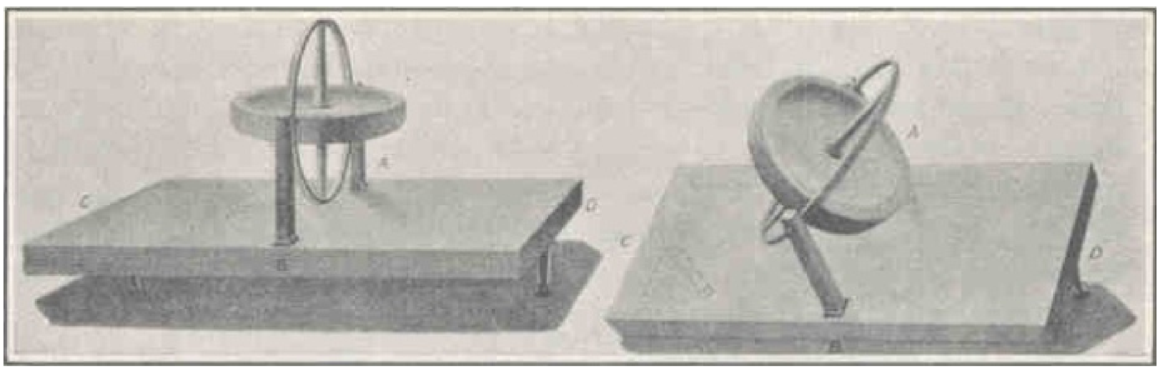

Figure 2.4 Illustration of precession [29]

Essentially, Sperry used a gyro to measure the rolling angle of the ship and eliminated it by aggressively energizing the motor to tilt the gyro wheel. The result is much better than the previous design that relies on the natural stabilizing effect of the gyroscope. This might be the first disturbance rejection control application in United States [31].

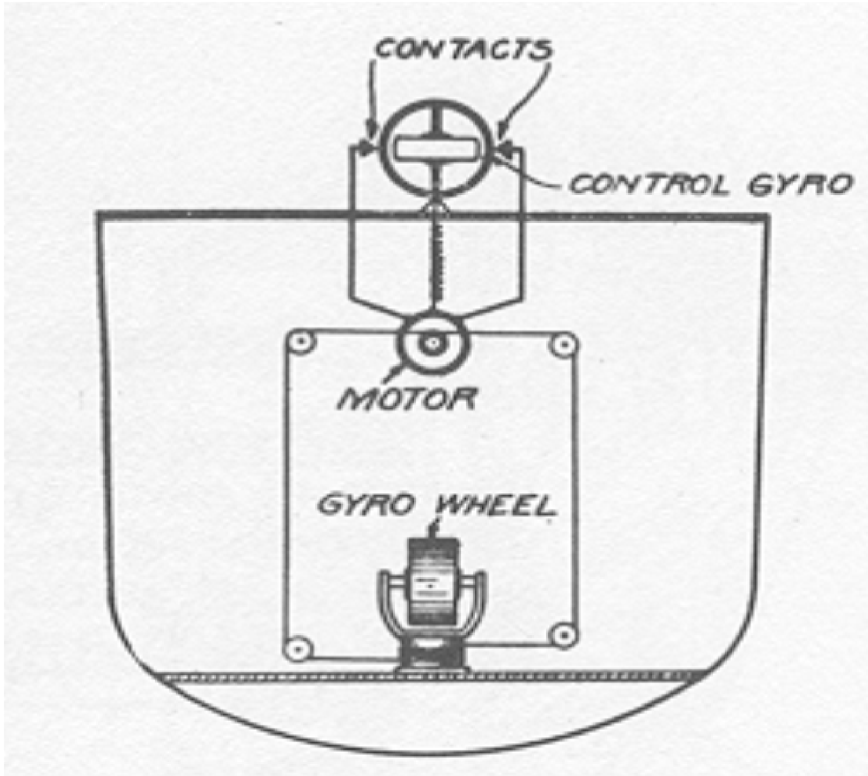

Figure 2.5 Sperry's gyro control design [30]

Harold S. Black, the inventor of negative feedback amplifier, tried to use feedforward to cancel the distortion and noise in signal transmission in 1923 [32]. Actually, this is another example of disturbance cancellation. According to his description, his design is shown in Figure 2.6. First the gain of the amplifier, μ, is inverted so that the equivalent input distortion could be obtained, before it is amplified by the same gain, μ, and subtracted from the original amplifier output to obtain an distortion free output signal.

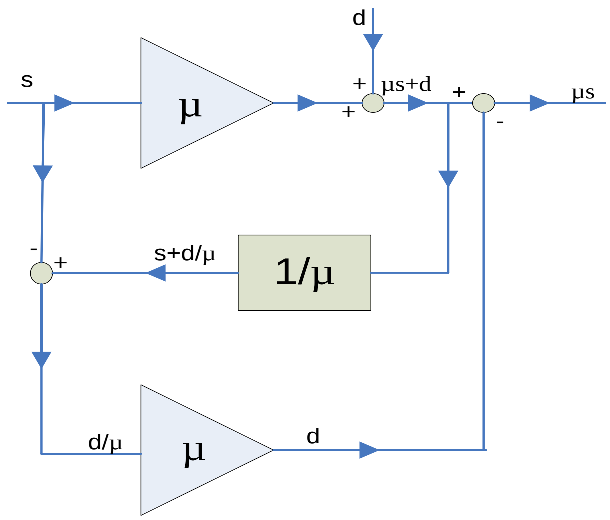

Figure 2.6 Black's feedforward design for cancelling distortion and noise

In this design, distortion is calculated and cancelled at the output side, leading to 40dB reduction of distortion in a single amplifier. However, there are weak points. The amplifier gain (system model) should be known exactly for the inverse to be accurate. In practice, however, such gain is not only not known exactly, but also changing with temperature and other factors in the operating condition, leading to a design that works well in laboratories where the gain of the inverse and the second amplifier can be readily adjusted, but impractical in the fields of operation.

Moore discussed a combined open-cycle closed-cycle system with load disturbance compensation in his 1951 paper, as illustrated in Figure 2.7 [33]. This system has open-loop feedforward for set point, close-loop feedback for error and feedforward for load disturbance (disturbance cancellation). However, this design relies on the knowledge to dynamics of the system. Feedforward for set point makes the output track the input well, feedback makes little correction to the small error between the output and input, and the disturbance compensator cancels the load disturbance out before it goes into the system. The system model and the measurement of the load disturbance are needed.

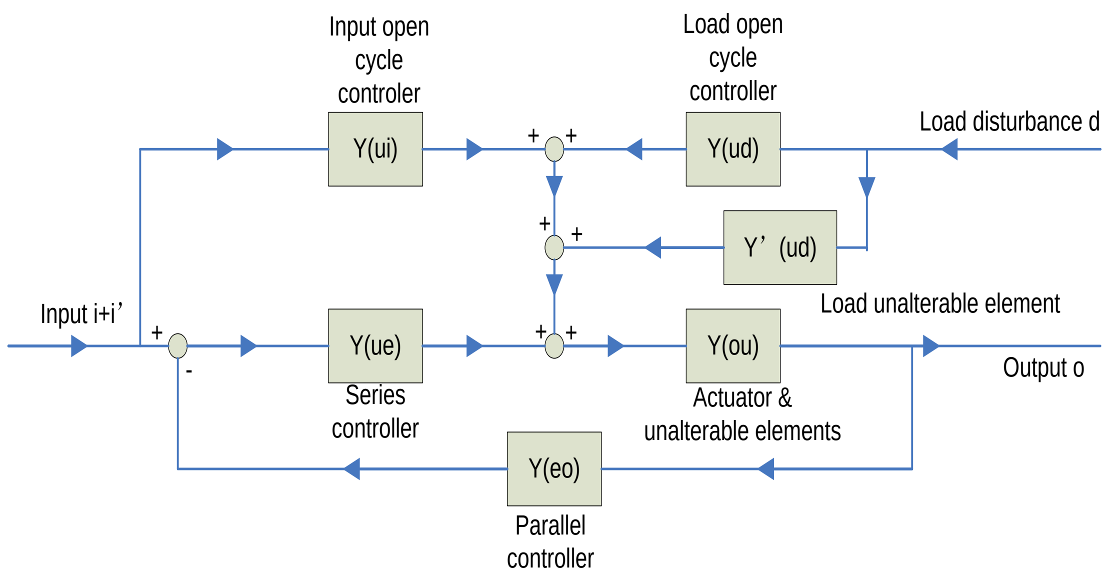

Figure 2.7 Open-cycle closed-cycle system with load disturbance compensation

Smith proposed a reasonable load disturbance compensator in 1960. In this design, load disturbance is not measured directly, but obtained by comparing a feedback signal and the input, as showed in Figure 2.8 [34]. Load disturbance is then cancelled at the input side. In this system, the plant model should be known well, while the access to the measurement of load disturbance is not needed.

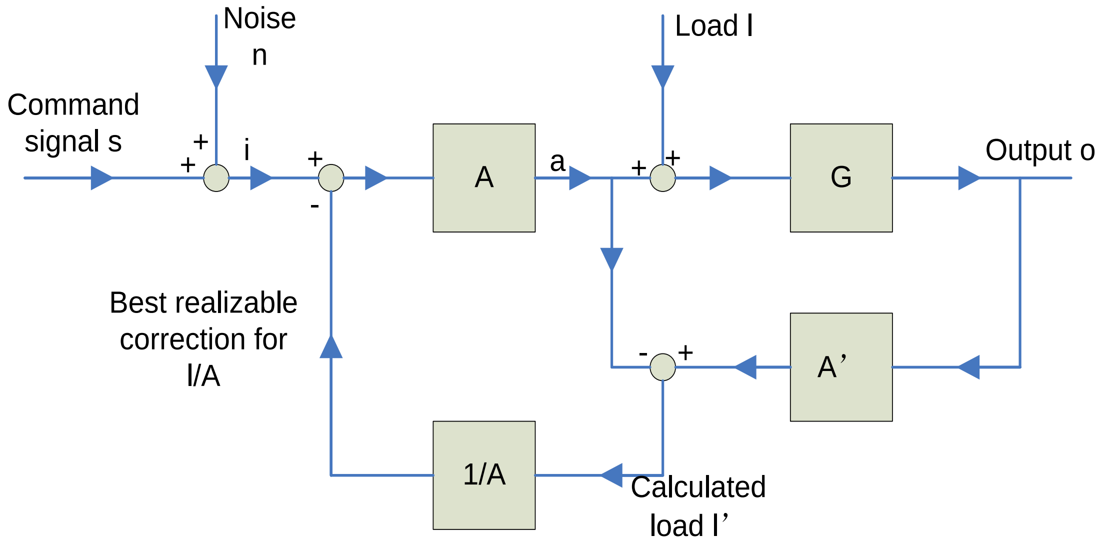

Figure 2.8 Smith's load disturbance compensator

C. D. Johnson presented a control method called Unknown Input Observer control (UIO control) in his 1971 paper. He used a novel control algorithm to obtain the estimation of unknown input disturbances and subtract them from control signal. *In many realistic control problems, the plant to be controlled is subjected to persistently acting external disturbances which are not known beforehand and are not accessible for measurement, but which do have a (more-or-less) known set of possible waveforms. In this paper it has been shown that if such disturbances can be modeled by solutions of some linear differential equation, then it is possible to construct a dynamical feedback controller which, by measuring only the available plant output y(t), can maintain accurate set-point regulation (or accurate servo-tracking) in the face of any such disturbances* [35].(Copyright by IEEE. Reprinted with permission.)

Obviously, UIO has the spirit of disturbance cancelling, but it still has drawbacks. Specifically, both the system model and disturbance model are required and it can only deal with the external disturbances [36].

Meanwhile, Japanese researcher developed a similar input disturbance observer (DOB) in 1987 without knowing C. D. Johnson's UIO. It is very similar in principle to UIO, with perhaps a simpler form [37-39]. Later on, the equivalence between UIO and DOB was established [39]. Figure 2.9 shows the structure of a disturbance observer for a motion system. Disturbance is estimated and then cancelled out. However, the model information is needed and only external disturbances can be estimated [40].

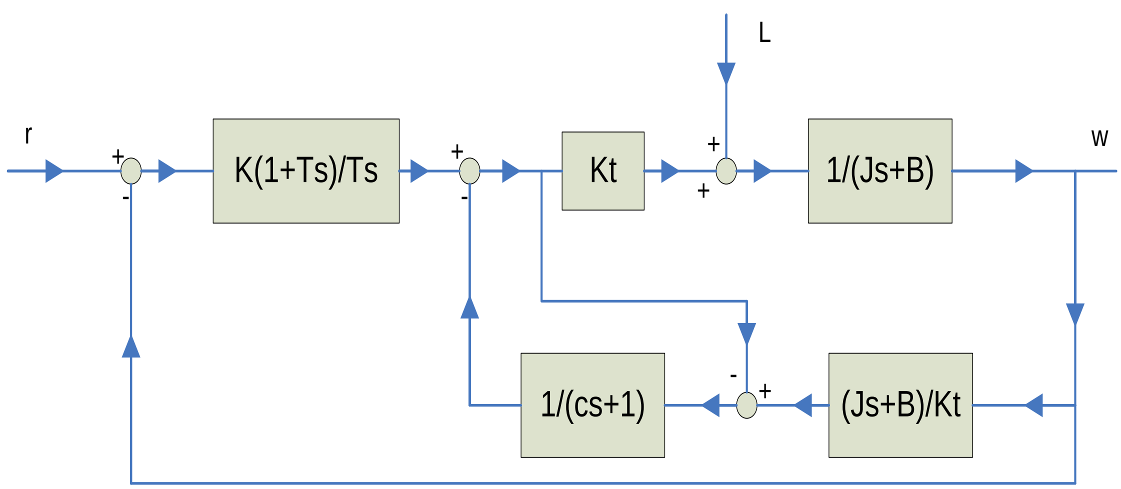

Figure 2.9 Structure of DOB (disturbance observer)

In S. J. Kwon and W. K. Chung's 2002 paper, a design of discrete perturbation observer (POB) is discussed. Figure 2.10 is the illustration of POB [41]. The perturbation observer not only estimates and cancels the perturbation, but also works as a model regulator, which makes the inner loop a nominal plant.

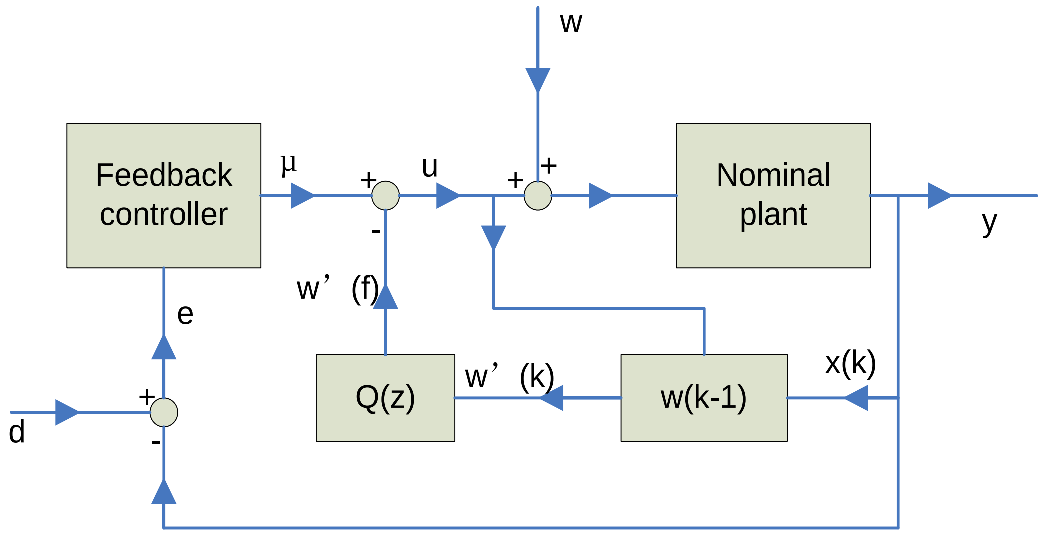

Figure 2.10 Structure of POB (perturbation observer)

Finally, the Extended State Observer (ESO) was proposed by Han in 1995 which regards both the internal dynamic uncertainties and the external disturbances as total disturbance, which is estimated it by treating it as a state, hence the name extended state. In one bold stroke, the problem of robust control, arising from the uncertainties in the system dynamics, and the problem of disturbance rejection become one single problem [42-44]. Han's ESO was further simplified and parameterized by Gao [45] in 2003.

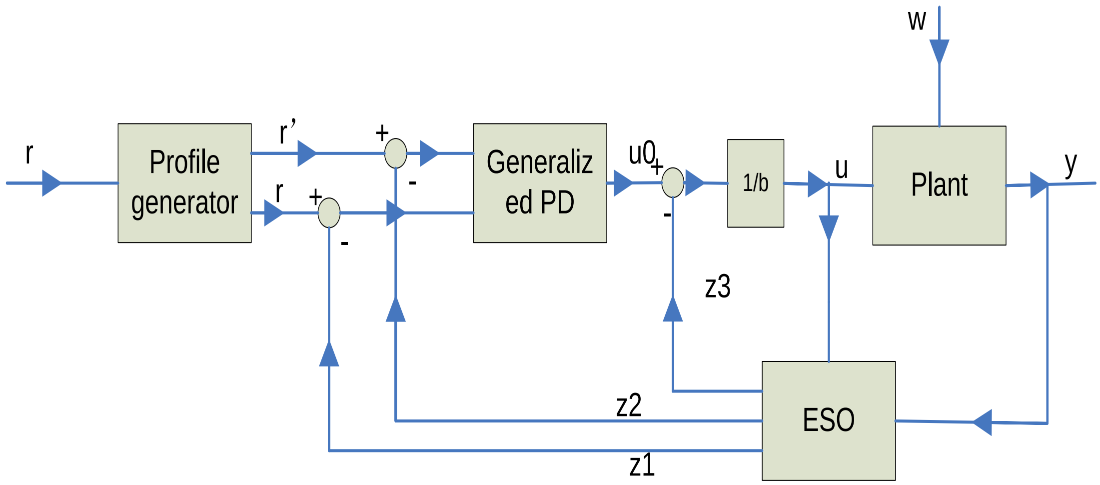

Figure 2.11 ADRC (active disturbance rejection control) system configuration

As shown in Figure 2.11 for a second order plant, the total disturbance (including input, output disturbances and model uncertainties) is estimated by ESO and then cancelled from the input side, reducing a complex, unknown, nonlinear plant to a simple double-integral one which can be easily controlled by a PD controller (for a second order system). Since the disturbance is actively estimate and cancelled, the resulting control system is denoted as Active Disturbance Rejection Control (ADRC). The main advantage of ADRC is that the exact model of the system and disturbance is not needed and the disturbance is cancelled out but it significantly affects the system performance.

2.3 Summary

In disturbance cancellation, the disturbances is first measured or estimated and then canceled at the input side before they affect the system. Compare to this, the feedback only design makes the correction after error has already occurred. So, in this sense, feedback is passive, while disturbance cancellation is active. In an ideal system whose plant model and disturbance model are known exactly, there is no need of feedback. Even in a practical system with disturbance cancellation, feedback should not play a major role but do little correction to the small error caused by the uncancelled disturbances and uncertainties.

Between the measuring and estimating methods in obtaining the disturbance information, the latter is more attractive for two reasons: 1) it doesn’t require any hardware change; 2) it could estimate not only the disturbances but also the dynamic uncertainties. With this knowledge, I gained great confidence in ADRC’s implementation in the electro-hydraulic servo control systems. Although there are models for hydraulic systems, there are still significant disturbances and uncertainties in hydraulic systems, which are also quite nonlinear, and this gives a great platform to test ADRC.

CHAPTER III

HYDRAULIC PROBLEM DESCRIPTION AND REFORMULATION

Electro-hydraulic servo system is a dynamic process. If the dynamic model of the system is obtained, the system can be simulated in computer software to see how it acts without practically running it. Afterwards, the controllers are designed according to the dynamic model and the best one is selected after being tested in the software. Hence, model description and analysis are very important.

In this chapter, the dynamics of the electro-hydraulic servo system is discussed and the nonlinear state space equations are obtained in section 3.1. The electro-hydraulic servo control problem is reformulated in section 3.2

3.1 Plant Dynamics

There are many kinds of electro-hydraulic servo systems, which can be generally divided to valve-controlled system [9] and direct drive system [4]. Valve-controller system uses proportional valve, while direct drive system does not. This thesis only focuses on the problem of the valve-controlled system. This is a high-order nonlinear system, which is used widely in industry.

3.1.1 Main Structure Of The Valve-Controlled System

Figure 3.1 shows the main structure of the electro-hydraulic system [9]. This is a SISO (Single-Input Single-Output) system. The input is the voltage u and the output is the displacement x_p.

First of all, the input voltage u causes a spool displacement x_v in a two-stage electro-hydraulic proportional servo valve. When the spool moves, the orifices in the valve are opened. Then, flow goes through one orifice from the valve to the cylinder and through another from the cylinder back to the valve.

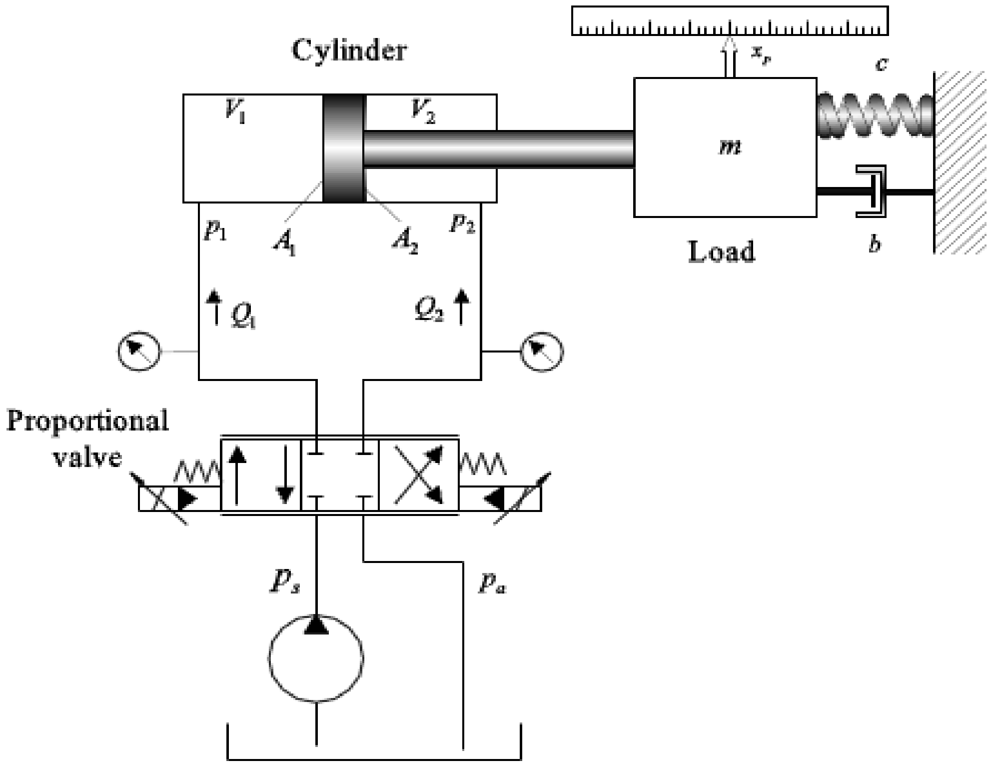

Figure 3.1 Main structure of electro-hydraulic system. From "Robust H-infinity control synthesis of an electro-hydraulic servo system," by Z. S. V. Milic and M. Essert, 2010, *ISA Transactions*. Copyright by Elsevier. Reprinted with permission.

The flow that goes into and gets out of the cylinder has two different pressures P_1 and P_2, at the piston side and rod side, respectively. P_1 and P_2 act on the piston and make the mass move.

3.1.2 Dynamics Of Proportional Valve

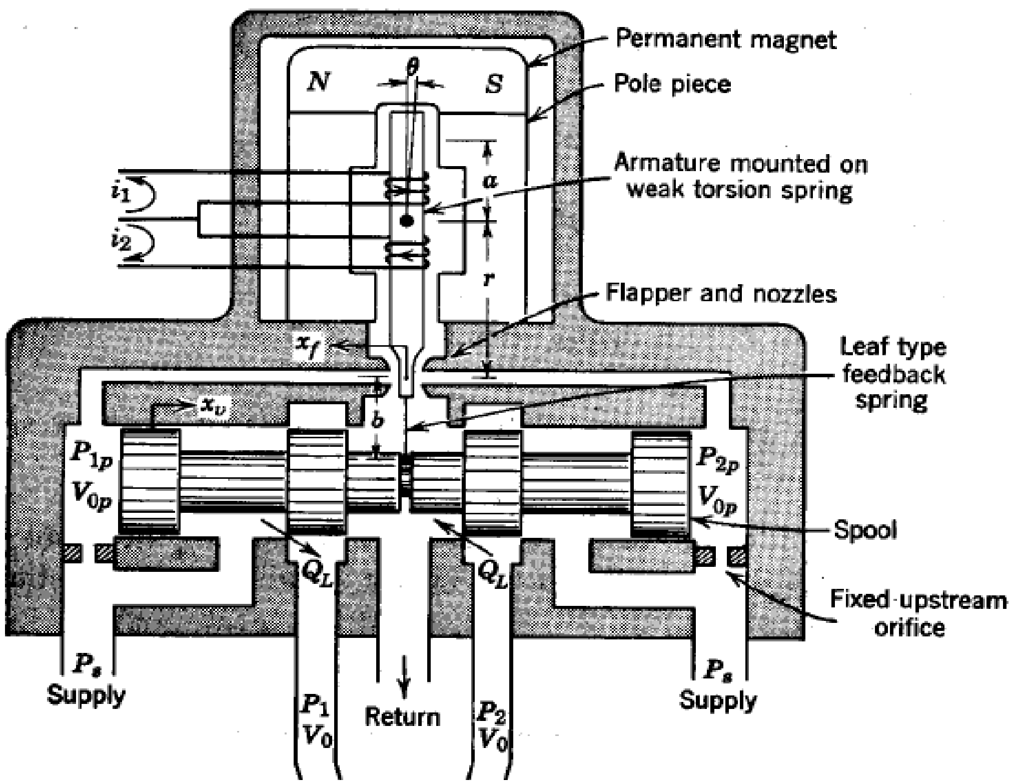

Figure 3.2 Two-stage electro-hydraulic servo valve. From *Hydraulic Control Systems,* by H. E. Merritt. Copyright by JOHN WILEY & SONS INC. Reprinted with permission.

The structure of the two-stage electro-hydraulic servo valve is shown in Figure 3.2 [46]. The sensitive flapper is driven by armature of an electro-magnetic torque motor, which causes the spool displacement.

The dynamics of proportional valve can be described by the following second-order linear differential equation:

$$\ddot{x}_v + 2\sigma_v\omega_v\dot{x}_v + \omega_v^2 = k_v\omega_v^2 u \quad (3.1)$$

Where k_v is the proportional valve gain, ω_v is the natural frequency, σ_v is the damping ratio of the proportional valve, x_v is the spool position and u is the input voltage.

3.1.3 The Nonlinear Relationship Between Flow And Pressure

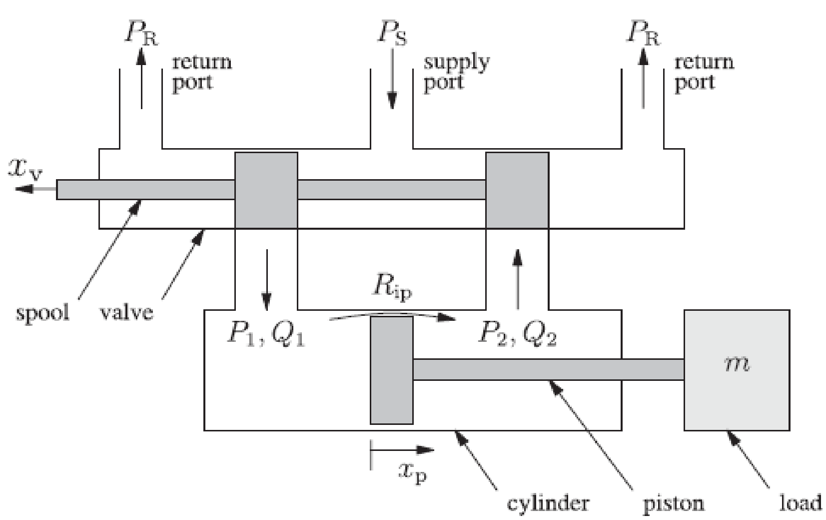

Figure 3.3 Combination of the proportional valve and the cylinder. From "Unified modeling and analysis of a proportional valve," by Bora Eryilmaz and Bruce H. Wilson, 2006, *Journal of the Franklin Institute*. Copyright by Elsevier. Reprinted with permission.

Figure 3.3 is the combination of the proportional valve and the cylinder [47]. When the spool moves, the flow goes into the cylinder and the pressures P_1 and P_2 act on the piston to make the mass move.

The equations of the flow through the proportional valve can be written as follows:

$$Q_1 = \begin{cases} C_v x_v \sqrt{(P_s - P_1)}, x_s \geq 0 \\ C_v x_v \sqrt{(P_1 - P_r)}, x_s < 0 \end{cases} \tag{3.2}$$

$$Q_2 = \begin{cases} C_v x_v \sqrt{(P_2 - P_r)}, x_s \geq 0 \\ C_v x_v \sqrt{(P_s - P_2)}, x_s < 0 \end{cases} \tag{3.3}$$

where P_1 and P_2 are the pressures at the piston side and rod side, respectively, P_s is the supply pressure, P_r is the return pressure and C_v is the valve coefficient for all the valve ports.

Hydraulic pressure behavior for a compressible fluid volume can be described by the following two equations:

$$Q_1 = A_1 \frac{dx_p}{dt} + \frac{V_{01} + A_1 x_p}{\beta} \frac{dP_1}{dt} \tag{3.4}$$

$$Q_2 = A_2 \frac{dx_p}{dt} - \frac{V_{02} - A_2 x_p}{\beta} \frac{dP_2}{dt} \tag{3.5}$$

where V_{01} and V_{02} are the original volumes of the piston side and the rod side of the cylinder, A_1 and A_2 are the annulus areas of the piston side and the rod side and β is the fluid bulk modulus. Rewrite equation (3.4) and (3.5):

$$\dot{P}_1 = \frac{\beta}{V_{01} + A_1 x_p} (Q_1 - A_1 \dot{x}_p) \tag{3.6}$$

$$\dot{P}_2 = \frac{\beta}{V_{02} - A_2 x_p}(-Q_2 + A_2 \dot{x}_p) \tag{3.7}$$

3.1.4 Motion Dynamics

The equation of motion dynamics of the piston can be obtained based on Newton's law of motion:

$$\ddot{x}_p = \frac{1}{M_t}(P_1 A_1 - P_2 A_2 - b\dot{x}_p - cx_p - F_l) \tag{3.8}$$

where M_t is the total mass of the piston and the rod, *b* and c are the viscous damping coefficient of the actuator and the load stiffness, respectively, and F_l is the external disturbance force.

3.1.5 Nonlinear State Space Equations

By defining the state variables as: $x_1 = x_v$, $x_2 = \dot{x}_v$, $x_3 = P_1$,$x_4 = P_2$, $x_5 = x_p$, $x_6 = \dot{x}_p$, the nonlinear model of the electro-hydraulic system can be written as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\omega_v^2 x_1 - 2\sigma_v \omega_v x_2 + k_v \omega_v^2 u \\ \dot{x}_3 = \frac{\beta}{V_{01} + A_1 x_5}\left(C_v x_1 \sqrt{\Delta P_1} - A_1 x_6\right) \\ \dot{x}_4 = \frac{\beta}{V_{02} - A_2 x_5}\left(C_v x_1 \sqrt{\Delta P_2} + A_2 x_6\right) \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = \frac{1}{M_t}(A_1 x_3 - A_2 x_4 - c x_5 - b x_6 - F_l) \end{cases} \tag{3.9}$$

where ΔP_1 and ΔP_2 are defined as:

$$\Delta P_1 = \begin{cases} P_s - x_3, x_1 \geq 0 \\ x_3 - P_r, x_1 < 0 \end{cases} \tag{3.10}$$

$$\Delta P_2 = \begin{cases} x_4 - P_r, x_1 \geq 0 \\ P_s - x_4, x_1 < 0 \end{cases} \tag{3.11}$$

As the nonlinear state space equations are obtained, the model of the electro-hydraulic system can be built in simulation software.

By observing the state space equations, we can conclude that this electro-hydraulic servo system is a sixth-order system and is nonlinear. Disturbances may go into the system in any part of the process and the load is variable. Hence, this electro-hydraulic servo control problem is first and for most a disturbance rejection problem. Traditional PID usually does not have good performance in this kind of highly nonlinear and disturbances involved systems. In feedback linearization, H_∞ control and sliding mode control, it is very complicated to build the controller, which is based on the knowledge of the plant model and the disturbance model. ADRC is designed to estimate the total disturbance including model uncertainties and external disturbances and cancel it from the input side. Hence, ADRC is selected as the solution for the electro-hydraulic servo system investigated in this thesis.

3.2 Hydraulic Problem Reformulation

After further observation, it is discovered that this electro-hydraulic servo system can be divided to two parts. If the pressure difference is defined as a new variable in the form of:

$$v = P_1 A_1 - P_2 A_2 \tag{3.12}$$

Then the system dynamics can be expressed in two parts:

$$\dot{v} = V(u) \tag{3.13}$$

$$\ddot{x}_p = \frac{1}{M_t}(v - b\dot{x}_p - cx_p - F_l) \tag{3.14}$$

where $V(u)$ represents the first four equations in (3.9), which is a complicated highly-nonlinear process and (3.14) represents the simple second order motion system.

Figure 3.4, Figure 3.5 and Figure 3.6 are the step responses of the pressure difference v with different step input voltages. Note that the response changes greatly when input voltage changes, indicating great complexity in nonlinear dynamics. To simply the design and achieve invariance of the system performance in the present of model uncertainties and disturbances, we treat such complex internal dynamics as a part of generalized disturbance which is to be estimated and cancelled by the control signal. In other words, ADRC is applied to this kind of electro-hydraulic servo system in this thesis.

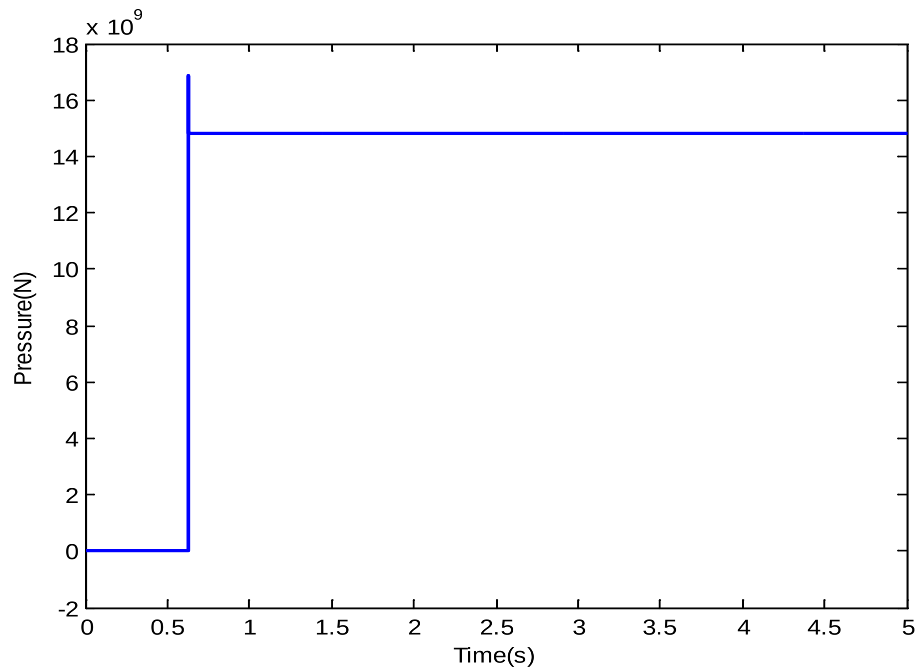

Figure 3.4 Step response of force difference (final value of u is 0.00005 V)

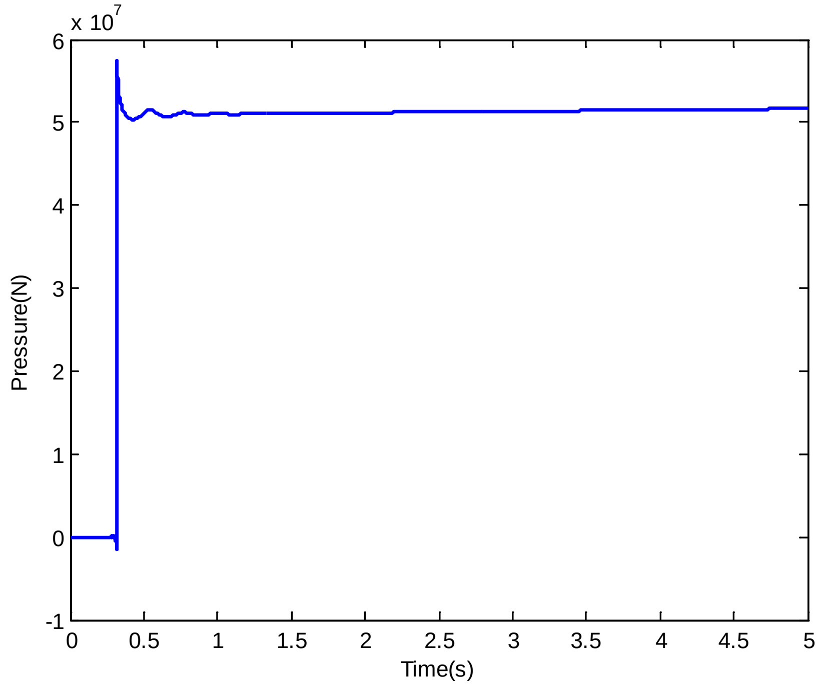

Figure 3.5 Step response of force difference (final value of u is 0.00010 V)

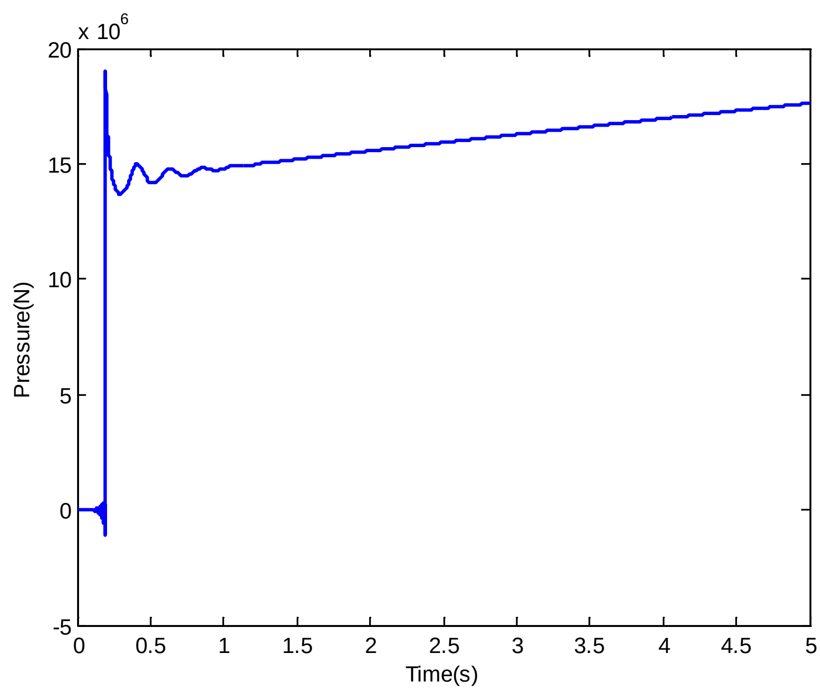

Figure 3.6 Step response of force difference (final value of u is 0.00020 V)

CHAPTER IV

ADRC CONTROL DESIGN

From the brief review of disturbance cancellation history is discussed in Chapter II, we know that ADRC (Active Disturbance Rejection Control) is one of the most popular disturbance cancellation control methods. Especially for a system with unknown disturbances and model uncertainties, ADRC has its own advantages. Meanwhile, hydraulic systems usually have many disturbances and uncertainties. ADRC may fit hydraulic systems perfectly.

In this chapter, control design of ADRC is described using a second order system as an example in section 4.1. A summary is made in section 4.2.

4.1 ADRC Control Design

ADRC is an advanced control technology which is becoming more and more popular in recent years. ESO (Extended State Observer), the most important part of ADRC, is used to estimate the total disturbance of the system and cancel it from the control signal before it affects the system [45].

A second order system is taken as an example, which could be expressed by the following differential equation:

$$\ddot{y} = bu + f(y, \dot{y}, w, t) \tag{4.1}$$

where y is the output, b is a constant, u is the input, f is the total disturbance including internal disturbance and external disturbance, w is the external disturbance and t is time. For simplification we use the notation

$$f = f(y, \dot{y}, w, t) \tag{4.2}$$

In this system, if the estimation of the total disturbance $\hat{f}$ can be obtained, the control signal then can be built according to the following equation:

$$u = \frac{u_0 - \hat{f}}{b} \tag{4.3}$$

where u_0 is a part of the control signal to be determined shortly. Then the system becomes:

$$\ddot{y} = u_0 - \hat{f} + f \tag{4.4}$$

Suppose that perfect estimation could be obtained:

$$\hat{f} = f \tag{4.5}$$

The system can be described as below:

$$\ddot{y} = u_0 \tag{4.6}$$

It is a pure double-integrator, which is without the external disturbance and internal uncertainties, and u_0 can be easily designed to meet performance specifications.

But, how do you obtain the estimation of the total disturbance $\hat{f}$? Here comes the essential part of ADRC, ESO. For a second order system, a third order ESO is designed as below:

$$\dot{z} = Az + Bu + L(y - \hat{y}) \tag{4.7}$$

$$\hat{y} = Cz + Du \tag{4.8}$$

Where $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ b \\ 0 \end{bmatrix}$, $C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$, $D = 0$, $L = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix}$.

Here $L = \begin{bmatrix}\beta_1\\ \beta_2\\ \beta_3\end{bmatrix}$ is used to place the poles of the ESO to make sure that the ESO is stable.

The ESO's state space equation can be expanded:

$$\begin{cases}\dot{z}_1 = z_2 + \beta_1(y - \hat{y})\\ \dot{z}_2 = z_3 + bu + \beta_2(y - \hat{y})\\ \dot{z}_3 = \beta_3(y - \hat{y})\end{cases} \tag{4.9}$$

Compared to the original system:

$$\begin{cases}\dot{y}_1 = y_2\\ \dot{y}_2 = y_3 + bu \quad (y_3 = f)\\ \dot{y}_3 = h \quad \left(\dot{f} = h\right)\end{cases} \tag{4.10}$$

If the ESO is stable and follows the system well, z_1, z_2, z_3 will be the accurate estimation of $y, \dot{y}, f$, respectively.

The great advantage of ESO over traditional State Observer is that the total disturbance is regarded as an extended state and is also estimated. To simplify the tuning problem, the three eigenvalues of the ESO are all placed at $-\omega_o$ [45], and the corresponding observer gain L is:

$$L = \begin{bmatrix}\beta_1\\ \beta_2\\ \beta_3\end{bmatrix} = \begin{bmatrix}3\omega_o\\ 3\omega_o^2\\ \omega_o^3\end{bmatrix} \tag{4.11}$$

Parameter ω_o here is the bandwidth of the observer. It is preferred to be large, hence the observer will be faster and observe the disturbance more quickly. But this bandwidth is limited for several reasons. For example, higher bandwidth will bring more noise; it is also constrained by the sampling frequency in a digital implementation.

For the control signal u_0, a simple PD controller usually sufficient, in the form of:

$$u_0 = k_p(r - y) + k_d(\dot{r} - \dot{y}) \tag{4.12}$$

$$k_p = \omega_c^2 \tag{4.13}$$

$$k_d = 2\omega_c \tag{4.14}$$

Hence, there are only two tuning parameters in this control method: ω_o and ω_c.

4.2 Summary

The working principle of ADRC in a second order system is described here. First, disturbances and uncertainties are estimated by the observer and cancelled from the input signal before going into the plant. This whole part, including ESO, can be regarded as a new plant, which should become a pure double-integrator ideally. Then a simple PD controller is implemented to control it. This PD controller is parameterized, hence the close-loop system has both poles placed at $-\omega_c$. For a traditional PID, the integral part is used for disturbance compensation. The integral part can help eliminate the steady state error. But PID does not have an observer and it can only react after an error takes place. Hence, traditional PID control is passive.

Next, the disturbance rejection ability of ADRC is shown in Chapter V, where ADRC and PID are compared.

CHAPTER V

SIMULATION

In this chapter, Matlab/Simulink is used to simulate the electro-hydraulic servo control system with both PID controller and ADRC. The building of the simulation model is shown in section 5.1. The simulation results for PID controller and ADRC are compared in section 5.2. Finally, some discussion is provided in section 5.3.

5.1 Setting Up The Simulation

As the state space differential equations have been obtained in Chapter III and the parameters of this system are shown in Table 5.1, the electro-hydraulic servo control system model is then built in Matlab/Simulink. Figure 5.1 is the nonlinear model built in Simulink according to the state space equations. Input1 is the voltage, Input2 is the load disturbance and Output is the mass displacement.

$k_v(m/V)$	1.05×10^6	$A_1(m^2)$	1.9635×10^{-3}
$\omega_v(rad/s)$	120.5	$A_2(m^2)$	9.4562×10^{-4}
σ_v	0.5	$V_{01}(m^3)$	2.9452×10^{-4}
C_v	2.863×10^{-9}	$V_{02}(m^3)$	1.4184×10^{-4}
$P_s(Pa)$	1.5×10^7	$M_t(kg)$	100
$P_t(Pa)$	1×10^5	$b(N \cdot s/m)$	700
$\beta(Pa)$	1.05×10^9	$c(N/m)$	75000

Table 5.1 Parameters in the electro-hydraulic position control system

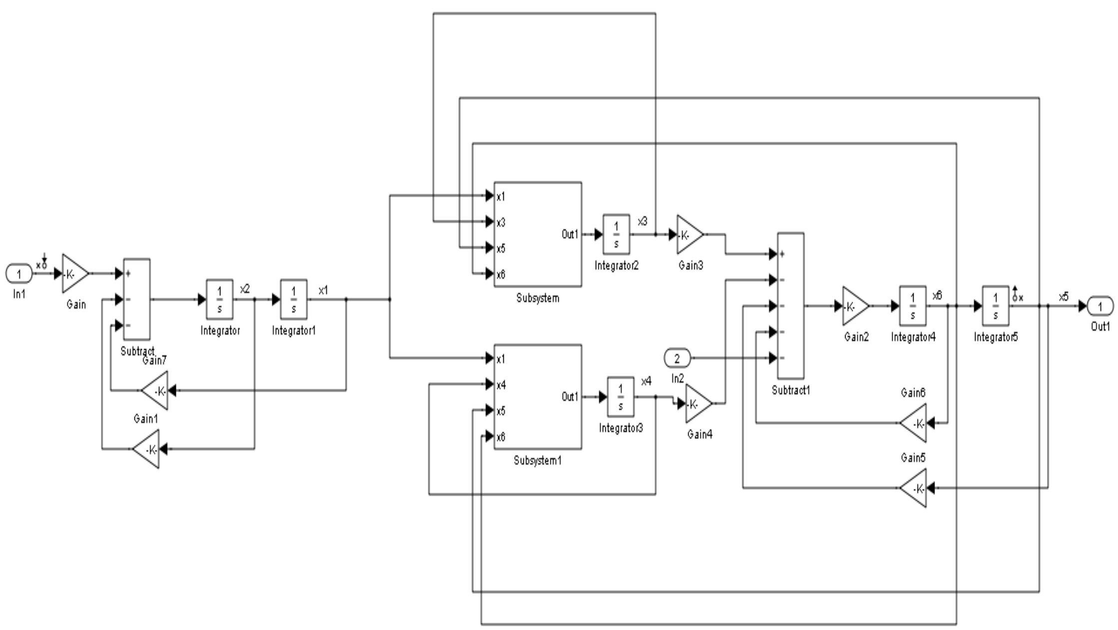

Figure 5.1 Plant model of the electro-hydraulic system

The whole plant model can be integrated into one block, making it a subsystem. Figure 5.2 is the subsystem block for the plant model.

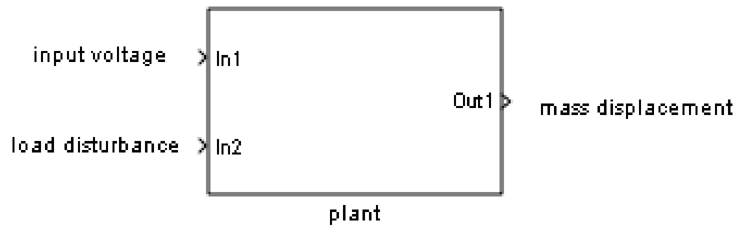

Figure 5.2 Subsystem block for the plant model

Then the PID controller and ADRC are both implemented in Matlab Simulink. Figure 5.3 is the system with ADRC and Figure 5.4 is the system with traditional PID controller.

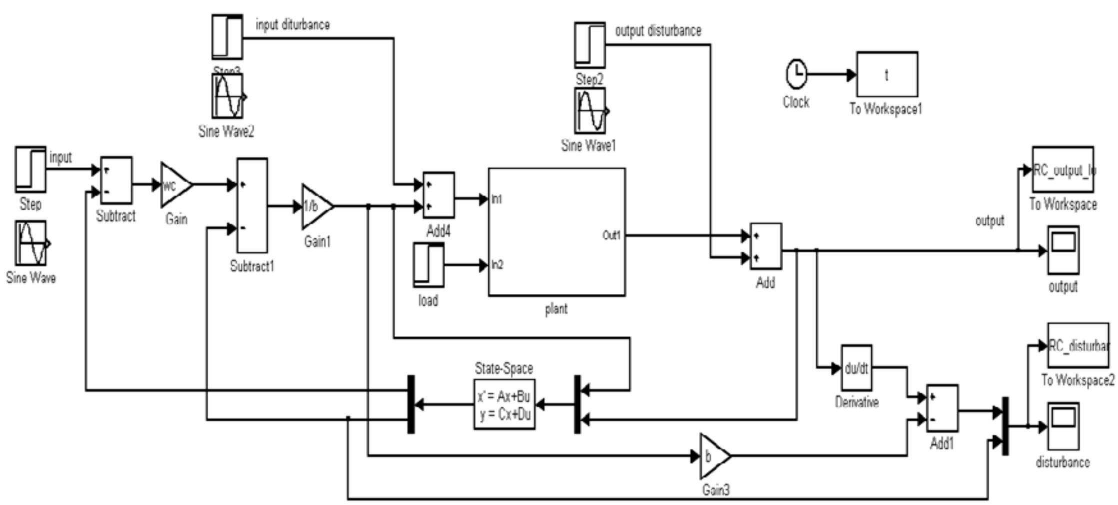

Figure 5.3 ADRC controlled system

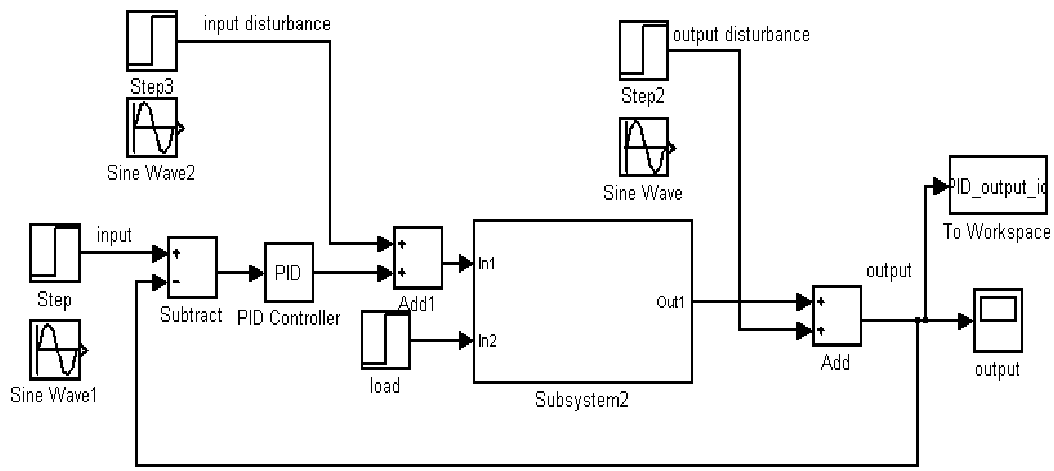

Figure 5.4 Traditional PID controlled system

5.2 Simulation Results

In this thesis, the electro-hydraulic servo system is reformulated as a second order system with disturbance, for which third order ADRC, shown in the previous chapter as an example, is first tried but the performance is not satisfactory. Second order ADRC is tried afterwards, the performance is more satisfactory. In this case, the system is force to behave like a first order system which means $\ddot{y}$ is regarded as a part of the disturbance. The ESO in the second order ADRC is second order and the controller is a simple proportional controller as shown in Figure 5.3. The three parameters of ADRC are:

$$b_0 = 10000$$

$$\omega_c = 15$$

$$\omega_o = 150$$

The performance of the closed-loop system with input disturbance (introduce in at 1.5s) is shown in Figure 5.5. In this simulation, load disturbance is also considered, which is as large as 16000N.

From Figure 5.5, it can be seen that ADRC has a good tracking and disturbance rejection performance even when the constant load is as large as 16000 N. The output is driven back to the set point very fast after being influenced by the disturbance. The control signal is very small.

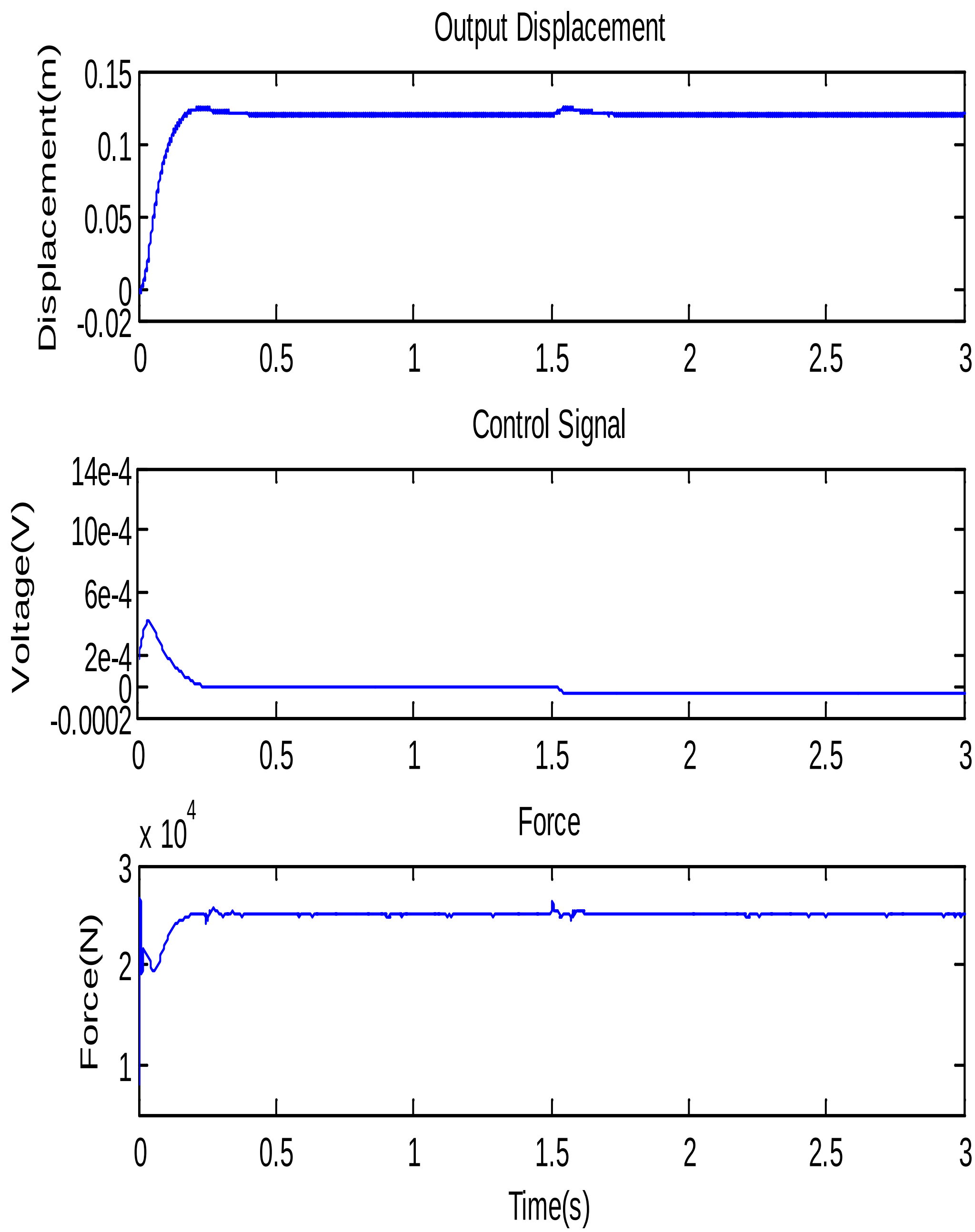

Figure 5.5 Performance of ADRC controlled system, corresponding control signal and corresponding force difference

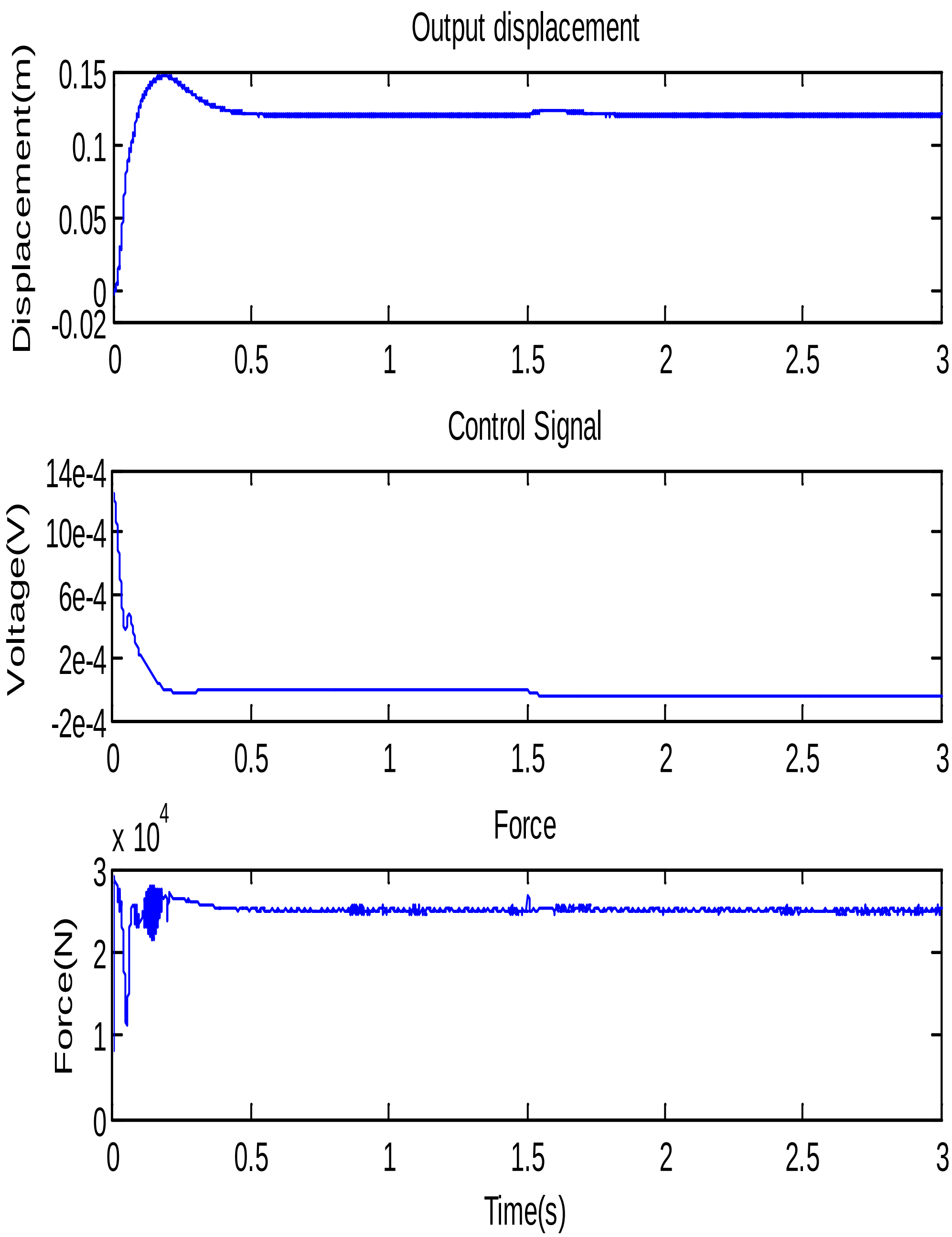

Figure 5.6 Performance of PID controlled system, corresponding control signal and corresponding force difference

With a traditional PID, tracking performances and disturbance rejection cannot be made satisfactory at the same time, after repeated attempts. Figure 5.6 shows load disturbance response in the PID system. Input disturbance of 16000N is introduced in at 1.5s. The parameters of PID are $k_p = 0.01, k_i = 0.08, k_d = 0.0002$. This is the best performance that could be obtained from a traditional PID controlled system, considering both tracking and disturbance rejection. It can be seen that this PID system's track and disturbance rejection performance are both worse than ADRC system and the control signal is even larger in PID system.

One may wonder: Why ADRC has a better performance than traditional PID controller? The essential reason is ESO (Extended State Observer). In this problem, this electro-hydraulic servo control system is regarded as a first order system, which can be described by the following equations:

$$\dot{y} = bu + f \tag{5.1}$$

$$f = f(y^{(n)}, y^{(n-1)}, \dots, y^{(2)}, y, w, t) \tag{5.2}$$

f here is the total disturbance, including the external disturbances and model uncertainties, n is the order of this system.

If ESO can estimate the total disturbance quickly and accurately, such disturbance can then be cancelled from the input side before it affects the system performance. That is, the process is reduced to a first order integrator. This can be illustrated by the following equations:

$$\hat{f} \approx f \tag{5.3}$$

$$u = \frac{u_0 - \hat{f}}{b} \tag{5.4}$$

$$\dot{y} = b \times \frac{u_0 - \hat{f}}{b} + f = u_0 - \hat{f} + f \approx u_0 \tag{5.5}$$

It should be checked whether the value of $\hat{f}$ estimated by ESO tracks the real total disturbance f accurately. $\hat{f}$ is the second output of the second order ESO and f can be obtained by this equation:

$$f = \dot{y} - bu \tag{5.6}$$

where y' and u are accessible in simulation and b is a known constant.

Figure 5.10 is the comparison of the disturbance $\hat{f}$ estimated by ESO and real total disturbance f. This is under the condition of 16000N load and an input disturbance coming in at 2.5s. It can be seen that the estimated disturbance $\hat{f}$ tracks the real disturbance f very well. Hence, the previous discussion of ADRC is verified.

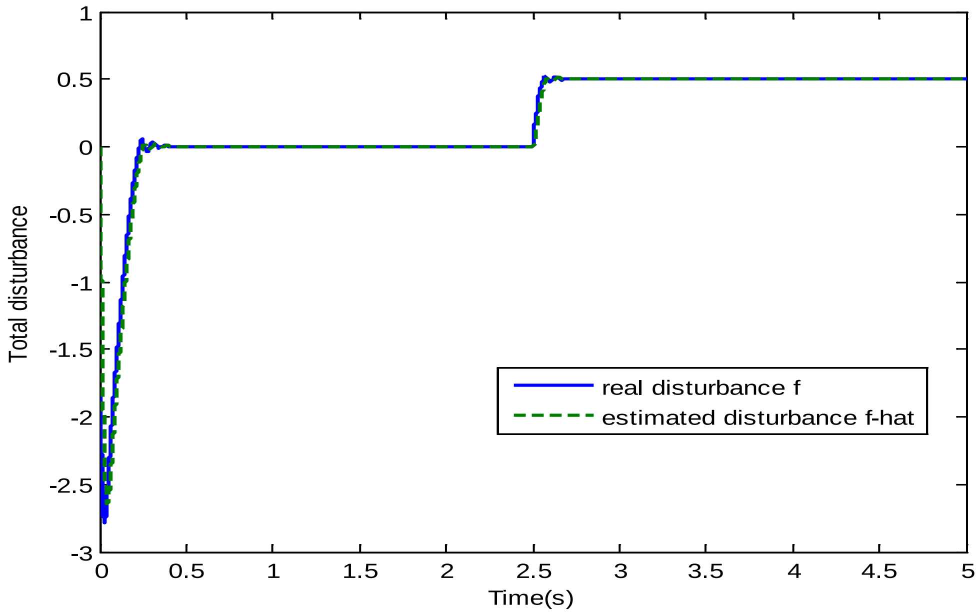

Figure 5.7 Comparison of ESO estimated disturbance and real disturbance

5.3 Discussion

From the simulation results, several remarks provided here.

Simplicity of choosing the variables for ADRC: In ADRC, there are totally three variables, b, ω_c and ω_o. If some knowledge of the system model is obtained, b might be found rather than tuned. Usually, ω_o is in the range of $1\omega_c \sim 10\omega_c$. Hence, things will become easy in deciding the values of the three variables of ADRC. On the contrary, traditional PID controller has three unrelated variables whose ranges are very large. Nonlinear PID, fuzzy PID and other advanced PIDs have even more variables.

Tracking and disturbance rejection performance: ADRC can perform both tracking and disturbance rejection very well, while traditional PID controller sometimes can make only one of them acceptable. The new “self-tuning PID” block in Simulink is used to find out best sets of PID parameters for different systems. This function block can only consider either tracking or disturbance rejection, but not both at the same time. Better tracking performance tends to make the disturbance rejection poor, and vice versa.

Appealing to intuition: According to the simulation study on how ESO tracks the real total disturbance, it could be said that the working principle of ADRC is very reasonable and intuitive. In this problem, the system is regarded as a first order system and all the other things in the system are regarded as disturbance. ESO tracks the total disturbance very well and cancels it from input side. This is done actively and it makes sense. The whole complicated process becomes a simple, pure integrator, while the traditional PID controller passively respond to output changes, leading to significant error.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

Based on the literature review of disturbance cancellation history, it is amazing to discover developments of this active control method from all over the world. Electro-hydraulic servo control system has many disturbances and model uncertainties and is nonlinear. A new advanced control method is needed. ADRC, a novel form of disturbance cancellation control, is then implemented in the electro-hydraulic system and simulation results are obtained. With the comparison to traditional PID controller, the reason why ADRC has a better performance is analyzed.

In this chapter, concluding remarks will be provided in section 6.1 and future work will be discussed in section 6.2.

6.1 Conclusions

From long ago, people gradually realized that if a system's disturbance can be obtained by certain methods and cancelled before it goes into the system, the performance will be much better. The precondition is that the disturbance is accessible. Because of this and the stability reasons, researchers proposed the dual-channel control, combining disturbance cancellation and feedback control together. Actually, disturbance cancellation and output feedback are not contradictory to each other. On the contrary, they can work together perfectly. Disturbance cancellation control eliminates the major part of the source that causes the output deviation and feedback corrects the remaining error. The stability condition is also satisfied by the feedback. But, in the real world, many disturbances are unknown and even not accessible. The old disturbance governor/compensator based on the measurement of the disturbance cannot be implemented widely in practice because of the additional sensor required. The invention and development of state observers give new vitality to disturbance cancellation. ADRC is one of the novel forms of disturbance cancellation. It combines ESO, which uses an extended state to estimate the disturbances and model uncertainties, and traditional PD controller.

From the simulation results, it can be seen that ESO can estimate disturbances quickly and accurately, giving ADRC a better performance than traditional PID controller in electro-hydraulic servo control system.

6.2 Future work

Based on the understanding of the principle of disturbance cancellation, Active Disturbance Rejection Control may not be restricted to ESO. Whatever disturbance information of system we have, and we have a lot, it could all be used to controller anticipate and preempt the effect of disturbances. Some states of the system can be obtained by measurement and we do not have to rely on ESO to obtain all the states. Hence, ESO's bandwidth could be reduced and the effects of noise could be reduced.

This idea of disturbance cancellation should be emphasized in future work as it's central to almost all control problems. In different control problems, the idea of active disturbance rejection could be realized in different, innovative ways.

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