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DEVELOPMENT OF HYDRAULIC LOAD SIMULATOR FOR FORCE CONTROL WITH HIGH PRECISION

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ABSTRACT

Nowadays, hydraulic actuators play an important role in a modern industry where controlled force or position with high accuracy is the most significant demand. This paper presents a new kind of hydraulic load simulator (HLS) for conducting performance and stability test in the bench system where force control is important. The system model consists of a hybrid hydro-electric actuator and another hydraulic circuit generating disturbances. For the purpose of improving force control performance of hybrid systems, a robust force controller using Quantitative Feedback Theory (QFT) technique applied to the HLS is also proposed in this paper. The controller is designed to satisfy the robust performance requirement, tracking performance specification, and disturbance attenuation despite uncertainties of HLS. Experiments are carried out to evaluate the effectiveness of the proposed control method applied for hydraulic systems even in the large varying perturbation.

KEY WORDS

Key words: Hydraulic system; Force control; Quantitative feedback theory (QFT)

NOMENCLATURE

$P(s)$	:	Transfer function of the nonlinear plants
$G(s)$	:	Cascade compensator - Controller
$F(s)$	:	Input filter transfer function
$y(t)$	:	Plant output
$r(t)$	:	Command input
V, D	:	Disturbances
$T(s)$	:	Closed-loop transfer function
$L(s)$	:	Opened-loop transfer function
$Dis(t)$	:	Disturbance source
ω	:	Frequency

INTRODUCTION

Hybrid actuation systems have a wide range of applications because of their advantages such as durability, high power, controllability, accuracy, reliability, etc ... To improve the stability and performance of the hybrid actuators, especially in dynamic loading process with unknown disturbances, some kinds of load simulator systems were presented. Su and Wang [1] presented a new kind of electro-hydraulic load simulator with high precision. The experiment results showed the effect on the way how to eliminate or reduce the disturbance torque and improve control performances of loading system. Li [2] carried out the thorough analysis and research on torque load simulator using electro-hydraulic servo control. However the control problem is very complicated because of the dynamic characteristics of the hydraulic load actuation systems are basically nonlinear and uncertain. The nonlinearities and uncertainties mainly come from the unstableness of some hydraulic parameters such as bulk modulus, compressibility of oil or viscosity of oil.

The Quantitative Feedback Theory (QFT) is ideally suited to feedback design for systems with large parameter uncertainties. The concept was first introduced by Horowitz in the early 1960s and continuously developed by him and others into an efficient robust control design technique [3]. QFT technique has been successfully applied to solve many engineering problems, including robot position control, flight control actuators and manufacturing systems. In improving performance of variable-displacement hydraulic vane pump, Thompson and Kremer [4] developed a robust controller via QFT technique. The simulation results showed that the closed-loop system response remained stable under variation in fluid bulk modulus and linkage areas parameters. Niksefat and Sepehri [5] succeeded in using nonlinear QFT technique to design a robust force controller and overcame many of nonlinearities and uncertainties existed in the experimental industrial hydraulic actuators.

This paper proposes a new testing model of hybrid actuator – hydraulic load simulator (HLS) which contains a hybrid hydraulic-electric actuator and a disturbance generator. Moreover, a robust force controller is also designed for the (HLS) using QFT technique. Therefore, it contains two parts: derivation of a nominal plant model with the uncertain bounds for HLS dynamics and a force control loop design based QFT. The controller is designed to satisfy the robust performance requirement, tracking performance specification, and disturbance attenuation requirement.

EXPERIMENTAL APPARATUS

The schematic diagram of the new HLS is shown in Fig. 1. The system hardware consists of a hybrid hydraulic-electric actuator, a computer included PCI-bus multifunction cards and another hydraulic circuit generating disturbances simulating the noises in the hydraulic hybrid systems. In this model, the hybrid hydraulic-electric actuator is an intelligent hydraulic system. This is a combination of AC servo motor (SGMGH-30PCA21), piston pump, reservoir and hydraulic control circuit. The operation at the speed which meets the machine requirements (flow rate and pressure) reduces power loss, and provides energy savings. The pressure oil line from the pump without a control valve minimizes the pressure loss and substantially reduces the heat generation of hydraulic fluid. About the operation of the hybrid actuator, the bidirectional rotational pump is used and driven by the AC servo motor so that the pump can supply pressured oil in both directions. The pump is well equipped as a hydraulic driving force. With the servo drive, the digital control parameter setting facilitates the operation of the system and its maintenance. In addition, to prove the effectiveness of the presented control method when the system operates in the real conditions, another hydraulic-electric circuit is applied for generating disturbance which is a combination of band-limited white noises and a sine wave noise. The simulink interface with compatible PCI cards is used to supply the noise signal for the AC servo motor (FMA-KN55), through a hydraulic control circuit and piston to generate the perturbation environment. A compression spring with 519 kN/m stiffness is used to connect the hybrid actuator and the disturbance generator. A load cell (YG38-T5) is used for obtaining the feedback force signal. The setting parameters for the HLS system are as shown in Table 1.

In the control strategy of the hybrid hydraulic-electric actuator, the deviation between the reference input signal and the force sensor signal is measured on the PC. Here, the proposed controller processes the data inputs and the control signal is sent from the PC to the servo drive to drive the AC servo motor (SGMGH-30PCA21) by using PCI cards, consequently forming a feedback control loop.

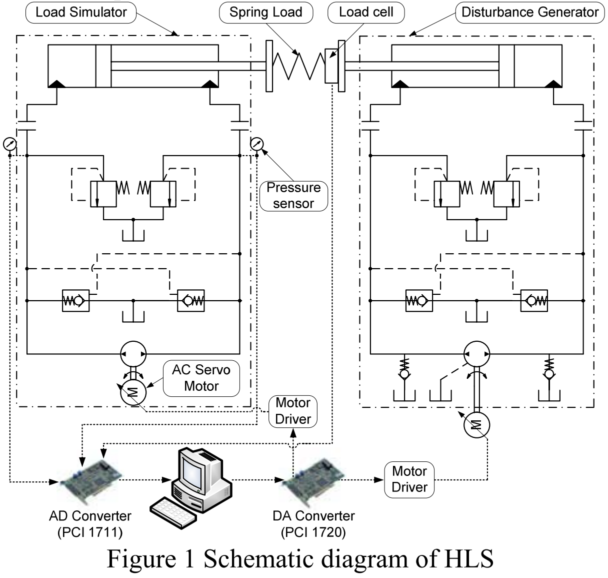

Figure 1 Schematic diagram of HLS

Table 1 Setting parameter for HLS System

System parameters	Parts		Meaning
	Load simulator	*Disturbance generation*	
AC Servo Motor	200	200	Power supply (Volt)
	2.5	2.2	Power (kW)

	18.6	26.18	Rate torque (Nm)
Pump	2500	2200	Speed (rpm)
	15	10	Displacement (cc/rev)
M (kg)	1000		Load
Cylinder parameters	63 x 35 x 150	55 x 35 x 100	Piston diameter x Rod diameter x Length of stroke (mm)
Spring (kN/m)	519		Environment stiffness
Relief Pressure (bar)	175		Relief valve cracking pressure

A PC (AMD Athlon 1.9 GHz) included two PCI-bus data acquisition & control cards (Advantech cards, PCI 1711 and PCI 1720) is used to receive, process feedback signals and generate the output signals to control the motors. The control algorithm is built within Simulink environment combined with Real-time Windows Target Toolbox of Matlab. Fig. 2 displays the experimental apparatus.

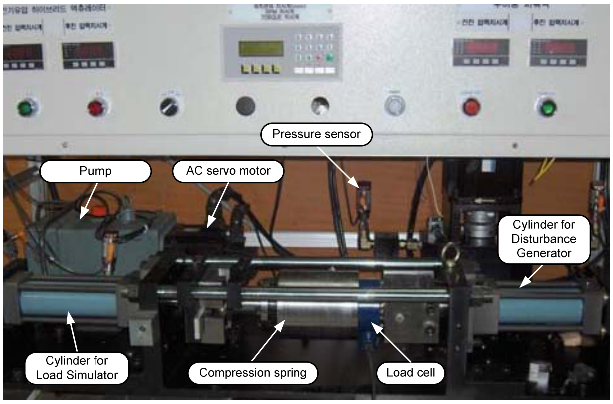

Figure 2 Photograph of HLS system

ROBUST CONTROLLER DESIGN

Quantitative Feedback Theory (QFT) is a unified theory that designs and implements robust control for a system with structure parametric uncertainty to satisfy the desired performance specifications, even when faced with the presence of disturbance, noise amplification or resonance.

The QFT method proposes as a general control strategy the two of freedom structure presented in Fig. 3. The output y(t) is required to track the command input r(t) and reject disturbances.

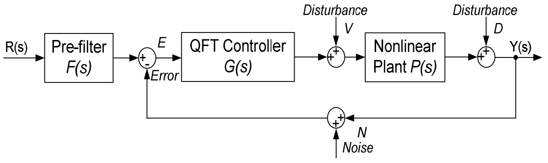

Figure 3 Structure of QFT algorithm

The controller *G(s)* is to be designed so that the variation of *y(t)* resulting from nonlinear plant uncertainties is within allowable tolerances and that the effects of the disturbances of *y(t)* are acceptably small. Also, the filter *F(s)* must be designed to achieve the desired tracking close-loop control ratio.

Model Identification

For the purpose of controller design, the derivation of linear time-invariant equivalent models is necessary. The first step in designing a robust QFT controller is thus to derive a family of uncertainties of the plant transfer function. An equivalent family of plants can be derived analytically, numerically from a plant model or directly from plant experimental input-output data.

In this study, a family of linear time invariant transfer functions for the HLS is obtained from experimental frequency responses of the system in the presence of significant uncertainty. Experimental frequency responses to a square input signal are carried out. The input signal is supplied to the driver of the AC servo motor in the load simulator part and then makes the cylinder impact on the spring-load sensing. Moreover, the maximum impact force to the load cell is 5 tonf. Therefore to avoid the damage to the load cell, the amplitude of the input signal is set to ±4.2 V at which the acting force to the load sensing measured is more than 4 tonf.

In the identification process, the experiment was done many times to obtain the gathering of the input and output data. To identify a family of uncertainties of the plant transfer function, the estimation of simple process models in MATLAB was used with the sampling time is 0.01s.

One sample experimental result is shown in Fig. 4. This result corresponds to the case when the maximum allowable control signal is applied to AC servo driver. As shown in the upper part of Fig. 4, the simulation and experiment results closely agree.

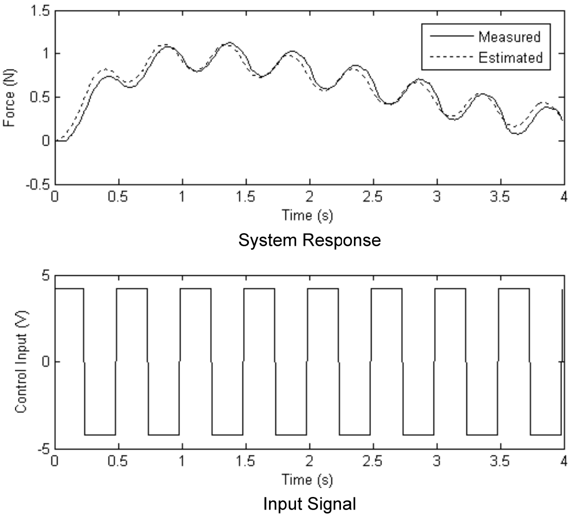

Figure 4 Identification of the system model

The HLS system can be presented by a family of second-order transfer functions as followings:

$$P(s) = \frac{k}{(1+as)(1+bs)} \tag{1}$$

here $k \in [3.97, 6.81]$; $a \in [0.75, 1.16]$; $b \in [0.75, 1.16]$;

QFT Controller Synthesis

The objective of this section is to design a robust force controller for the HLS that is represented by the uncertainty transfer function (1). In QFT, for tracking performance requirement, the strictly proper controller, *G(s)*, and a strictly proper pre-filter, *F(s)*, (Fig. 3) are to be designed base upon the stability and system performance's specifications. In this case, the HLS system should fulfil the following control criterions:

- Settling time = 1.5 [s]
- Maximum percentage of overshoot $\le 2[\%]$

In the case study, the bounds for tracking specifications correspond to the trajectory defined by the responses to the step input. The time responses $y_u(t)$ and $y_l(t)$ in Fig. 5 represent the upper and lower bounds, respectively. For a satisfactory design, an acceptable response *y(t)* must lie between these bounds. The modeling of a desired transmittance *T(s)* is discussed in detail by Horowitz [3].

After using an iteration process to find acceptable models, we have the following T_l and T_u functions:

$$\begin{aligned} T_u(s) &= \left| \frac{3479s^2 + 6.737e004s + 2.384e005}{s^4 + 94.04s^3 + 5220s^2 + 7.017e004s + 2.396e005} \right| \\ T_l(s) &= \left| \frac{26.54s^2 + 74.82s + 46.68}{s^4 + 17.67s^3 + 64.28s^2 + 96.76s + 47.11} \right| \end{aligned} \tag{2}$$

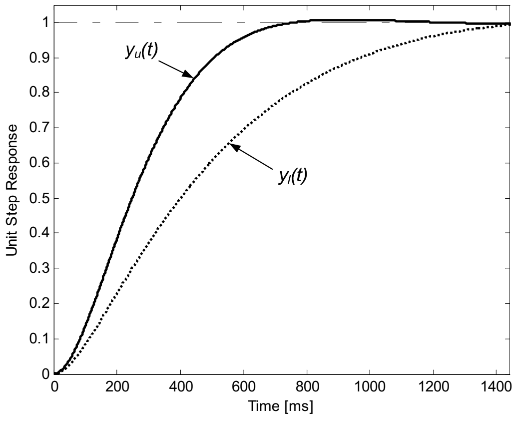

Figure 5 Tracking bounds in the time domains

Therefore, the QFT force control loop of the HLS system is designed how the signal robust tracking meet the acceptable range of variation with respect to a reference signal as follows:

$$|T_l(j\omega)| \le |T(j\omega)| \le |T_u(j\omega)|, \quad \omega \ge 0 \tag{3}$$

where *T(s)* is the closed-loop transfer function:

$$T(s) = \frac{F(s)G(s)P(s)}{1+G(s)P(s)} \tag{4}$$

In QFT approach, there are two control objectives. The first is the closed-loop robust stability which must be checked with reasonable margins. By the Nyquist criterion, closed-loop stability is retained as long as the loop gain does not cross the point -1 under uncertainty. The robust stability is presented by a forbidden region about the origin which is enclosed by an M-locus in the Nichols chart. Hence, an approximately of M = 1.4 (3 *dB*) gain margin for the closed-loop system is given by:

$$\left| \frac{L(j\omega)}{1+L(j\omega)} \right| \le M = 1.4, \quad \omega \ge 0 \tag{5}$$

where *L(s)*, the opened-loop transfer function, is defined

$$L(s) = P(s)G(s) \tag{6}$$

The second control objective is closed-loop disturbance attenuation. For disturbance rejection at plant output, the sensitive reduction problem has to be solved. Therefore, the upper tolerance is imposed on the sensitive function. Here, a constant upper bound to limit the peak value of disturbance amplification is considered as follows:

$$\left| \frac{1}{1+L(j\omega)} \right|_{\max} \le M_D(\omega) = 1.2, \quad \omega \ge 0 \tag{7}$$

Inequalities (3), (5) and (7) impose constraints on nominal loop gain $|L_0(s)|$ (where $L_0(s) = P_0(s)G(s)$, and $P_0(s)$ denotes the nominal plant transfer function). These constraints are used to determine the tracking performance, robustness and output disturbance rejection boundaries on the Nichol chart at each critical frequency as ω= 0.01;0.05;0.1;0.5;1.5;5;10;50;100 rad/s. A feedback design satisfies these bounds if for each critical frequency the corresponding value of the loop gain is on or above the performance boundary, output disturbance boundary and to the right of or on the robustness forbidden region.

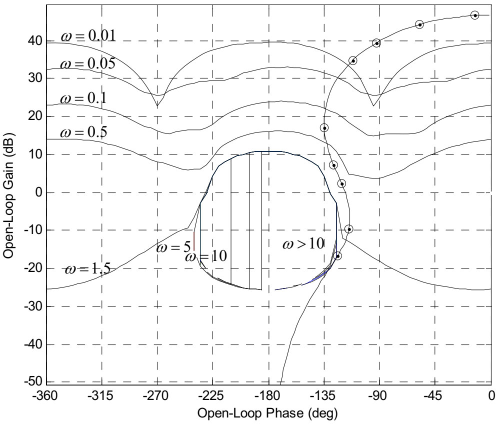

Figure 6 Superposition of all bounds

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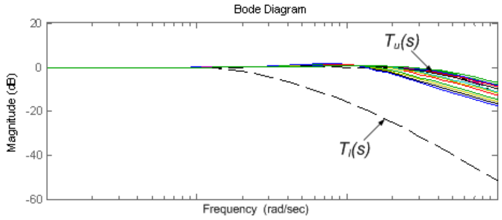
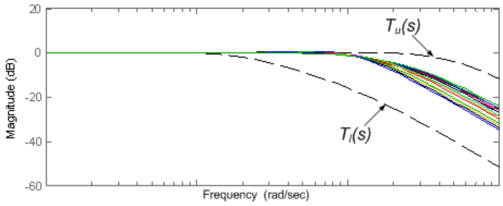


a) Robust tracking performance without filter



b) Robust tracking performance with filter F(s)

Figure 7 Robust tracking performance

The generated QFT bounds (by constrains (3), (5) and (7)) and the final loop shaping for the HLS are shown in Fig. 6. Based on the above analysis, the QFT robust controller is determined:

$$G(s)=\frac{621150.4154(s+7.528)}{s^2+583.7s+1.475e005} \tag{8}$$

The final step in QFT design process is the selection of the pre-filter $F(s)$. Design of a proper function $L_o(s)$ guarantees only that the variation in $|T(j\omega)|$ is less than or equal to its constraint (3).

Fig. 7.a shows the closed-loop frequency response of the HLS system not lay between the upper and the lower tracking performance boundaries of $T_l(j\omega)$ and $T_u(j\omega)$. Therefore, the purpose of the pre-filter is to position $\ln T(j\omega)$ within the frequency domain specifications. The pre-filter was found:

$$F(s)=\frac{14.0425}{s+14.45} \tag{9}$$

The effect of the pre-filter is illustrated by comparing closed-loop frequency response both with and without a pre-filter. From Fig. 7, it is clear that all tracking specifications are satisfied in frequency domain.

EXPERIMENTAL RESULTS

The QFT control algorithm and the conventional PID controller which is used to control the HLS system is built by the combination of Simulink and Real-time Windows Target Toolbox of Matlab and connected to Advantech cards. Fig. 8 displays the proposed control scheme applied to the HLS. The sampling time was set to be 0.001s for all experiments. Furthermore, in order to prove the effectuality of the proposed controller, a disturbance source containing the band-limited white noises and the sine wave noise (Fig. 8) is generated real time during the system operation as given:

$$Dis(t)=A\sin(\omega t)+Rnd(t) \tag{10}$$

where: A,ω are amplitude, frequency parameters of the sine wave; *Rnd(t)* is the random white noise signal.

All the disturbance parameters are changed to generate the small or large perturbation as shown in Table 2. The noise signal performed in (10) is sent from the computer to the AC servo drive of the disturbance generation part by the DA converter (PCI 1720). Then the controlled AC servo motor (FMA-KN55) with the hydraulic control circuit and piston are used to create the perturbation environment for the load simulator part in testing the control performance (see Fig. 1 and Fig. 8). Furthermore, the noise signal generated in (10) is added to the signal from the system output with a chosen gain to make a challenge for the force control problem.

At first, the small disturbance was generated to make comparisons of HLS using different controllers. The experiments were done with step reference input. In case of the HLS using traditional PID, the PID coefficients must be tuned by experience and trials to get the tracking performance in the acceptable range.

Table 2 Disturbance Parameters

Disturbance Kinds			Small Disturbance	Large Disturbance
Sine wave	Amplitude	Volt	0.4	0.8
	Frequency	Hz	5	2
White Noise	Power	Volt	0.00005	0.00015
Sampling time	T	sec	0.001	0.001

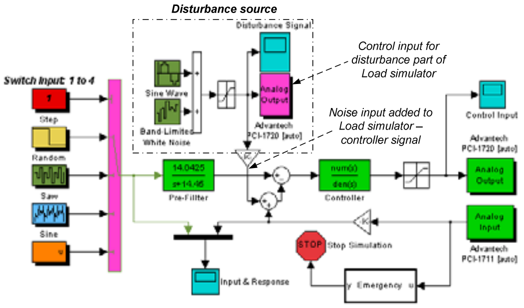


Figure 8 Simulink control diagram for HLS

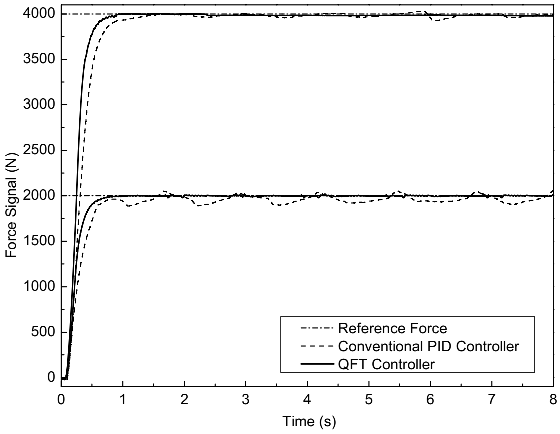


Figure 9 Step responses of HLS using PID and QFT – In case of small disturbance

Fig. 9 is the force responses with respect to step reference input. From the results, it shows that although the PID coefficients were tuned by trials, the control performance is worse than in case of using the QFT controller. Moreover, the effect of perturbation on the HLS makes the PID controller is unable to track the reference input with the allowable tolerance of error. It is shown clearly when the HLS operates in the large noise environment. Fig. 10 displays the control signals and the force response of HLS in case of step reference input and the working condition had large disturbance. These results show that conventional controller with fixed gains does not yield reasonable performance over a wide range of operating conditions. Hence, the robust force controller described in section 4 is implemented to overcome the above control problems.

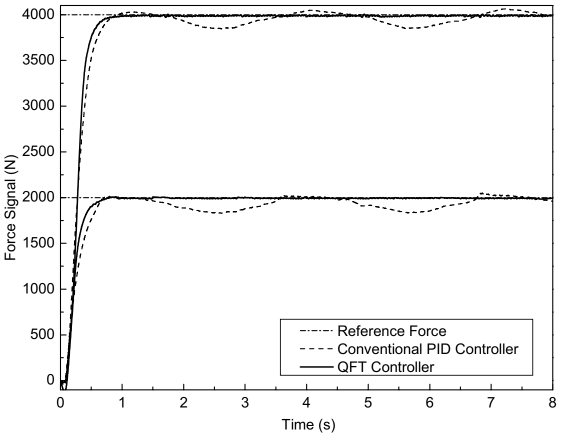


Figure 10 Step responses of HLS using PID and QFT – In case of large disturbance

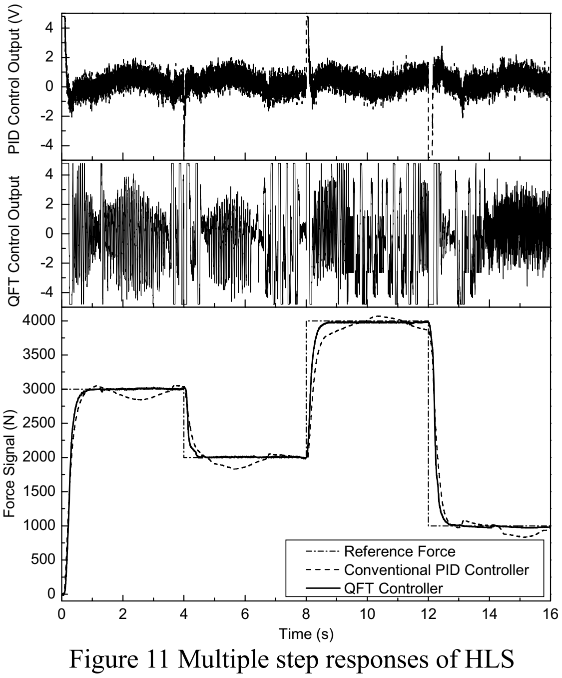


Figure 11 Multiple step responses of HLS – In case of large disturbance

In order to make the comparison between the conventional PID and the QFT controller for different set-point reference inputs, the multiple step signals, is also investigated. Fig. 11 is the responses of the HLS between using the PID and the QFT controllers. The results prove that, in case of different setting-points, the responses of the system using proposed controller is more stable than the conventional one. It is clear that a good force regulation is realized in the case of using QFT to design a robust force controller.

CONCLUSIONS

This paper presents a new kind of HLS which is very convenient for conducting performance and stability test for control force of hydraulic hybrid systems. A robust force control using the QFT design technique was developed and successfully applied to the HLS. The input pre-filter transfer function F(s) and proper controller G(s) are designed to satisfy the required specifications of robust stability, robust tracking and disturbance attenuation.

The experimental evaluation compared with the conventional PID controller prove convincingly that the QFT controller could achieve good tracking with respect to different reference input signals and in case of variation of disturbances.

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