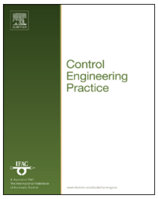
Control Engineering Practice 26 (2014) 51–71

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac



Pressure prediction on a variable-speed pump controlled hydraulic system using structured recurrent neural networks

Ergin Kilic[a,*], Melik Dolen[b], Hakan Caliskan[c], Ahmet Bugra Koku[d], Tuna Balkan[e]

[a] Suleyman Demirel University, Department of Mechanical Engineering, Room: E-4, Isparta 32260, Turkey
[b] Middle East Technical University, Department of Mechanical Engineering, Room: A-142, Ankara 06800, Turkey
[c] Middle East Technical University, Department of Mechanical Engineering, Room: G-135, Ankara 06800, Turkey
[d] Middle East Technical University, Department of Mechanical Engineering, Room: C-209, Ankara 06800, Turkey
[e] Middle East Technical University, Department of Mechanical Engineering, Room: F-211, Ankara,06800, Turkey

ARTICLE INFO

Article history:
Received 20 February 2013
Accepted 5 January 2014
Available online 6 February 2014

Keywords:
Pump controlled hydraulic system
Pressure dynamics
Long-term pressure prediction
Structured recurrent neural networks
Nonlinear system identification
Kalman filtering

ABSTRACT

This paper presents a study to predict the pressures in the cylinder chambers of a variable-speed pump controlled hydraulic system using structured recurrent neural network topologies where the rotational speed of the pumps, the position and the average velocity of the hydraulic actuator are used as their inputs. The paper elaborates the properties of such networks in extended time periods through detailed simulation- and experimental studies where black-box modeling approaches generally fail to yield acceptable performance. As alternative estimation techniques, both linear- and extended Kalman filters are considered in this paper. The estimation properties of the devised network models are comparatively evaluated and their potential application areas are discussed in detail.

1. Introduction

Fluid power transmission/control is commonly preferred over its electrical counterpart in many applications such as aircrafts, excavators, presses, mining- and agricultural machinery due to several well-justified reasons including the ability to generate large forces at higher speeds (with a high power-to-weight ratio), long operation life (in harsh environments), and easy heat dissipation of moving elements by means of hydraulic transmission oil. In *electro-hydraulic servo-systems* (EHSSs), the hydraulic power is either controlled by throttling principle (using servo-valves) or by volumetric control principle (via adjusting the rotational speed of a constant-displacement pump by a servo motor or via adjusting the pump displacement by a swash plate). The former principle offers good dynamic behavior at the expense of substantial energy losses at the flow control device. On the other hand, the latter principle yields increased efficiency with a poor dynamic response.

When the emphasis is placed on the high power transmission with low energy losses (i.e. cost-effectiveness), variable-speed pump-controlled hydraulic systems are generally preferred in the drive systems of the contemporary machine systems (Helbig, 2002; Helduser, 2003; Lovrec, Kastrevc, & Ulaga, 2008; Lovrec & Ulaga, 2007). However, there exist some critical problems such as the compressibility of the hydraulic fluid, friction, and leakage in the actuator. Due to compressibility, the dynamic behavior of hydraulic system becomes highly nonlinear while the friction and leakage in the hydraulic actuator poses difficulty in the model development and control efforts for such systems.

To achieve the control objectives in such systems, the control outputs (or states) such as pressure, actuator force, position, velocity and flow-rate are measured via instruments. Among those states, the pressures in cylinder chambers of the EHSSs are specifically needed to implement a closed-loop force and/or position control or to estimate disturbances on the hydraulic actuator. To be specific, some studies (Guan & Pan, 2008; Guo, Liu, Liu, & Li, 2008; Kaddissi, Kenne, & Saad, 2011; Mohanty & Yao, 2011; Pi & Wang, 2011; Yao, Bu, Reedy, & Chiu, 2000) in the current state-of-the-art use pressure measurements to control accurately the position of the hydraulic actuator via advanced techniques such as adaptive robust control, sliding-mode control and cascade control. However, the measurement of hydraulic (actuator chamber) pressures decreases reliability and increases the cost/complexity of the overall system due to extra sensors and interface circuitry incorporated to the system. Therefore, the number of dedicated pressure sensors has to be minimized so as to reduce the overall cost along with the sensor-related malfunctions. Hence,

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[*] Correspondence to: Mechanical Engineering Department, Suleyman Demirel University, Cunur, 32260 Isparta, Turkey. Tel.: +90 246 211 1230;
fax: +90 246 237 0859.

E-mail addresses: erginkilic@sdu.edu.tr (E. Kilic), dolen@metu.edu.tr (M. Dolen), chakan@metu.edu.tr (H. Caliskan), kbugra@metu.edu.tr (A. Bugra Koku), balkan@metu.edu.tr (T. Balkan).

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http://dx.doi.org/10.1016/j.conengprac.2014.01.008

Nomenclature

A_A	hydraulic cylinder cap end side area
A_B	hydraulic cylinder rod end side area
$\mathbf{A}$	system matrix (continuous time)
b	viscous friction coefficient
$\mathbf{B}$	input matrix (continuous time)
$\mathbf{b}$	bias vector
C_i	internal leakage coefficient of the pump
C_{ea}	external leakage coefficient at port A
C_{eb}	external leakage coefficient at port B
$\mathbf{C}$	output matrix (continuous time)
D_p	pump displacement
$\mathbf{e}$	prediction error vector
f_L	hydraulic force transmitted to the load
F_c	Coloumb friction
$\mathbf{F}$	nonlinear vector function
$\mathbf{f}$	system matrix of operating-point model
g	gravitational acceleration
$\mathbf{G}$	input matrix (discrete-time)
$\mathbf{H}$	measurement matrix
$\mathbf{I}$	identity matrix
k	discrete time index
m	load mass
n_{1o}	offset drive speed of pump 1
n_{2o}	offset drive speed of pump 2
n_1	dynamic drive speed of pump 1
n_2	dynamic drive speed of pump 2
n_{1t}	total drive speed of pump 1
n_{2t}	total drive speed of pump 2
N	number of data sample
P_A	hydraulic pressure in chamber A
P_B	hydraulic pressure in chamber B
P_L	load pressure
$\mathbf{P}$	posteriori estimate error covariance matrix
$\mathbf{P}^-$	priori estimate error covariance matrix
p_{sum}	desired sum pressure value
q_{p2A}	flow rate of the pump 2 outlet port
q_{p2B}	flow rate of the pump 2 inlet port
q_{p1A}	flow rate of the pump 1 outlet port
q_A	flow rate in chamber A
q_B	flow rate in chamber B
$\mathbf{Q}$	process noise covariance matrix
$\mathbf{R}$	measurement noise covariance matrix
T	sampling period
u	process input
$\mathbf{u}$	process input vector
v	hydraulic cylinder velocity
V_A	volume of hydraulic oil in chamber A
V_{A0}	chamber A initial volume
V_B	volume of hydraulic oil in chamber B
V_{B0}	chamber B initial volume
$\mathbf{W}$	weight matrix
x	hydraulic cylinder position
$\mathbf{x}$	state vector
x_{ref}	reference position
$\hat{\mathbf{y}}$	model output vector
$\mathbf{y}$	output vector
β	bulk modulus of hydraulic fluid
$\mathbf{\Phi}$	state transition matrix
$\boldsymbol{\varphi}$	regression vector
γ	hydraulic cylinder area ratio
λ	offset pump speed ratio
$\boldsymbol{\theta}$	model parameter vector
ψ	conversion factor between p_{sum} and n_{2o}
$\mathbf{\Psi}$	activation vector function

the objective of this paper is to predict the long-term pressure dynamics of a variable speed pump controlled hydraulic system via neural networks without the introduction of any extra sensors. Due to nonlinear nature of the hydraulic system, a *structured neural network* (SNN) is proposed as the solution of this challenging long-term pressure prediction problem at hand. Eventually, the paper investigates the feasibility (and conditions) of replacing the "physical" pressure sensors in variable-speed pump controlled hydraulic systems by these SNN based estimators which are to serve as "soft sensors."

The rest of the paper is organized as follows: After Section 1, a variable-speed pump controlled hydraulic system and its model is introduced in Section 2. Section 3 considers the use of classical estimation methods (including open-loop state observers and Kalman filters) on the prediction problem at hand. The following section focuses on the design of SNN architectures to predict the cylinder chamber pressures using black-box- and gray-box modeling approaches. Section 5 illustrates the practical use of the SNN (as devised in Section 3) on the hydraulic experimental test set up. Finally, some concluding remarks are presented in Section 6.

2. Pump controlled hydraulic system and its model

2.1. Experimental setup

The experimental test setup used in this study was originally constructed for the evaluation of state feedback control techniques on a hydraulic system via a servo-valve or a variable-speed pump (Caliskan, 2006). This test set up is illustrated in Fig. 1 while its circuit schematic is presented in Fig. 2. The dark lines represent the variable-speed pump controlled circuit and the gray lines denote the valve controlled circuit. The (quick) coupling connections 1, 2, and 3 are used to switch between two different modes. Since the pressure prediction of the variable-speed pump controlled hydraulic system is to be investigated; only the relevant portion of the circuit is taken into account in the present study. The components of the test setup are listed in Table 1.

In the setup, a double-acting asymmetric cylinder serves as the actuator that is rigidly connected to a steel plate. This plate is guided by two sliders at both ends to restrict the rotation of the actuator. Apart from the friction acting on the seals of the actuator and the support bearings; the weight of the steel plate

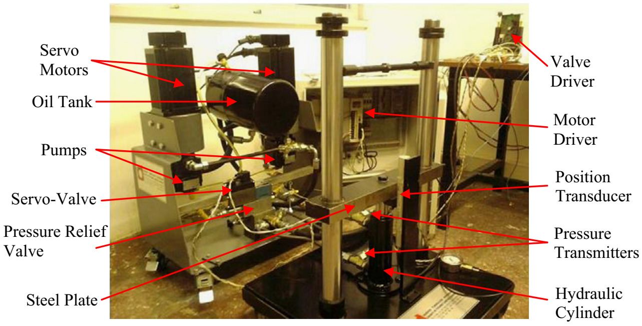

Fig. 1. View of the experimental test setup (Caliskan, 2006).