

NONLINEAR SYSTEM IDENTIFICATION OF HYDRAULIC ACTUATOR FRICTION DYNAMICS USING A FINITE-STATE MEMORY MODEL

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ABSTRACT

We present a finite-state memory model for parametric system identification of the lip seal friction process in a hydraulic actuator. The performance of the finite-state memory model is compared with two Hammerstein type models using experimental results.

1. INTRODUCTION

Lubricated sliding lip seals are important components in many hydraulic devices, such as actuators, solenoid valves, etc. The requirements imposed by today's high precision machines motivates the precise simulation of friction between these seals and sliding components, and there has been recent efforts to model the friction process using system identification techniques [1, 2].

Figure 1 shows a schematic diagram of a typical hydraulic actuator. The movement of the shaft of the actuator is controlled by regulating the pressure difference between chamber A and B through the hydraulic port. The lip seal keeps the lubricant from leaking out of the high pressured chambers while guaranteeing a smooth sliding of the shaft. A modeling of the input-output relationship between the velocity of the shaft $v(t)$, and the friction between the lip seal and the shaft is required for the design of reliable lip seals.

The approach in [1] uses a model based on the physics of the system. However, the complexity and

nonlinearity of friction, which depends on many parameters, such as the viscosity of the lubricant, characteristic of lip seal material, roughness of the sliding surfaces, hydraulic pressure, ambient temperature and relative velocity between the surfaces, etc [1, 3, 4], makes it very difficult to derive a practical model with not too many parameters with clear interpretation.

In [2], a different approach is used to model the system, in a sense that they does not seek model parameters related to physical parameters. As a result, models much simpler in structure, yet quite satisfactory in performance were obtained. In [2], a Hammerstein model and a Parallel model are introduced. A Hammerstein model is a nonlinear model, which assumes that the nonlinearity of the system can be separated from system dynamics, and can be described by the equation

$$f[k] = H(q^{-1}) \cdot g(v[k]),$$

where q^{-1} is a delay operator, $g(\cdot)$ is a static nonlinear function, $H(q^{-1})$ is the transfer function of the linear system dynamics, and $v[k]$ and $f[k]$ are the input and output of the model, respectively. The nonlinear function $g(\cdot)$ was parameterized by using wavelet representation of $g(\cdot)$, and MA (moving average) model was used for the linear system $H(q^{-1})$. The Parallel model was derived by a parallel connection of two Hammerstein models. The idea of Parallel model is to use a priori information about the lip seal. A theoretical steady state model which illustrates the nonlinear relationship between the velocity of the sliding shaft and the friction of the lip seal in a hydraulic actuator has been given in [3]. Given the physical parameters of the hydraulic actuator, the model provides a steady state nonlinear relationship between the velocity of the shaft and friction force that the seal experiences. In Parallel model, the nonlinear function of one of the two parallel Hammerstein model is replaced with the theoretical steady state model, and the difference between the theoretical model and the actual velocity/friction

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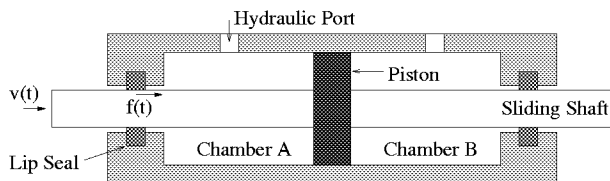


Figure 1: Schematic diagram of a hydraulic actuator. $f(t)$: the lip seal friction, $v(t)$: velocity of the shaft.

relationship is complemented by the other one of the two Hammerstein model in parallel. The parallel model can be described by the equation

$$f[k] = H_1(q^{-1}) \cdot d(v[k]) + H_2(q^{-1}) \cdot g(v[k]),$$

where $d(\cdot)$ is the theoretical nonlinear model of lip seal friction, $g(\cdot)$ is the nonlinear mapping function, and $H_1(q^{-1})$ and $H_2(q^{-1})$ are linear systems. An LMS algorithm is used to identify the model parameters. "For more details, see [2]."

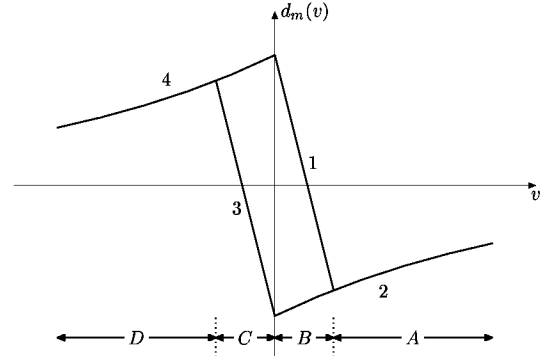
However, these models do not exploit the characteristic of the friction process caused by the deformation of the lip seal. In this paper, we present a *finite-state memory model* of the friction dynamics. The performance of the model is compared with the performance of the Hammerstein type models in [2] using experimental results.

2. FINITE-STATE MODEL

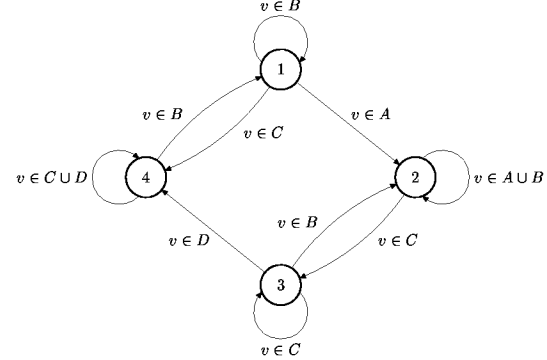
The hydraulic actuator in Figure 1 is driven by an eccentric drive system to generate periodic velocity and friction signals. Figure 4 shows sample plots of the velocity signal $v(t)$ and friction signal $f(t)$; (a) $72^\circ F$, 50 psi, 1 Hz, (b) $130^\circ F$, 50 psi, 1 Hz. Note that all the signals are periodic with period 1 sec, which corresponds to the duration of one cycle of the eccentric drive system. Also note that all signals, especially the velocity signals, have very high frequency components, which can be attributed to *frictional vibration* [3].

As shown in Figure 4, the relationship between $v(t)$ and $f(t)$ is highly nonlinear. The nonlinear relationship becomes more clearly visible when we see Figure 3, phase space trajectory plots of velocity and friction signals. These plots have a very important interpretation. From the plots, we can see that the friction value at a particular time depends not only on the value of velocity $v(t)$, but also the previous values of friction signal or history of the trajectory. This is due to the deformation of the seal when it is rubbed against the shaft which is moving back and forth. When the shaft is moving in one direction, the seal is deformed toward the direction the shaft is moving by the frictional force between the seal and the shaft. But, when the shaft changes its direction, the seal recovers its original shape and then is deformed toward the other direction. Thus, the friction signal depends on the current state of the seal. Therefore, it is obvious that if a model can remember the current state of the system, it would be able to estimate the friction signal from the input velocity signal.

This leads to a new *finite-state model* with simple



(a) Finite-state memory model.



(b) State transition diagram.

Figure 2: Finite-State Memory Model

memory illustrated in Figure 2 (a)

$$f(t) = d_m(v(t)),$$

where

$$d_m(v) = \begin{cases} f_1(v) & \text{for } (v, f) \text{ on line 1;} \\ f_2(v) & \text{for } (v, f) \text{ on line 2;} \\ -f_1(-v) & \text{for } (v, f) \text{ on line 3;} \\ -f_2(-v) & \text{for } (v, f) \text{ on line 4,} \end{cases}$$

$f_1(v) = a \cdot v + f_{\max}$, $f_2(v) = -f_{\max} \cdot e^{-\lambda v}$, $a < 0$, $f_{\max} > 0$, and $\lambda > 0$. $d_m(\cdot)$ is a nonlinear function with four states. The model switches from one state to another according to the rule described in Figure 2 (b). The transition from state 4 to state 1 occurs when the shaft changes its direction. At the intersection of state 4 and 1, even though the velocity is zero, the friction value is nonzero because of the deformed seal. The upper half of state 1 represents the time period when the seal recovers its original shape. The lower half of state 1 represents the time period when the seal is being deformed toward the opposite direction, and the model enters state 2 after the shaft completely change

its direction. The frictional vibration occurs in state 2 and 4. The transition from state 2 to 3, and 4 occurs in a similar manner.

3. EXPERIMENTAL RESULTS

We now compare the results of finite-state memory model with the Hammerstein model and Parallel model in [2]. In the simulation of the Hammerstein and Parallel model, Daubechies wavelet basis function of order 3 $\psi(\cdot)$ [7] was used, and the highest resolution used was $m = -1$, where

$$\psi_{m,n}(v) = 2^{-m/2} \psi(2^{-m}v - n),$$

where $\psi(\cdot)$ is Daubechies mother wavelet function. The order of $H(q^{-1})$, $H_1(q^{-1})$, and $H_2(q^{-1})$ were all 8.

Figure 5 shows the simulation result of Hammerstein and Parallel models. The result shows that both of the Hammerstein and Parallel models estimated the lip seal friction signal quite closely, but the Parallel model has better performance. Figure 6 shows the simulation result of finite-state memory model. As expected, finite-state memory model outperformed the Hammerstein model and Parallel model for both of $72^\circ F$ and $130^\circ F$ cases; finite-state memory model estimated the overall waveform of the friction signal more closely and the estimated friction signal is less noisy. Furthermore, finite-state memory model estimated the ‘frictional vibration’ much better than the Hammerstein model and Parallel models do. To show this, the details of the estimated friction signal of Parallel model is compared with the estimated friction of finite-space memory model in Figure 7. As shown in Figure 7 (a), the general shape of the estimated friction signal of Parallel model converges to the actual friction signal very well, but it fails to model the frictional vibration. On the contrary, as shown in Figure 7 (b), the finite-state memory model successfully estimate the frictional vibration as well as the general waveform of the frictional signal.

4. CONCLUSION

In this paper, a finite-state memory model for the non-linear system of the friction process of lip seal in hydraulic actuator have been developed. Examination of phase space trajectory plot of $v(t)$ and $f(t)$ suggested the finite-state memory model, and a state transition algorithm for this model is derived.

The performance of this model is compared with Hammerstein model and Parallel model. The simulation results showed that finite-state memory model

has a greatly improved performance over those models. Overall, Hammerstein model and Parallel model worked well. However, these models failed to model the frictional vibration. On the other hand, finite-state model successfully modeled the friction signal including the frictional vibration.

5. REFERENCES

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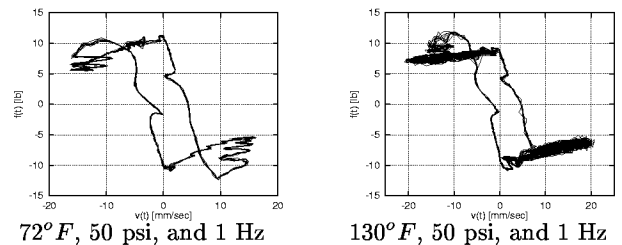


Figure 3: A phase space trajectory plot of velocity and friction signals.

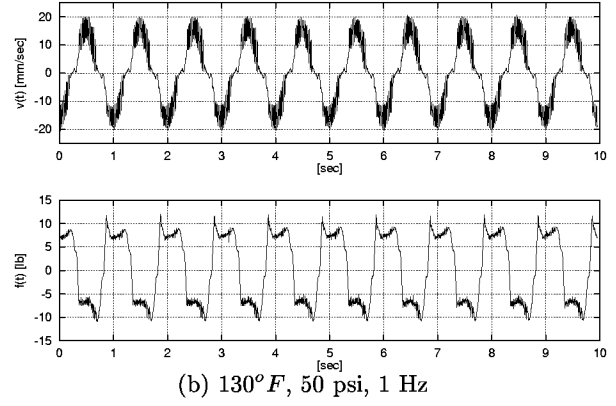
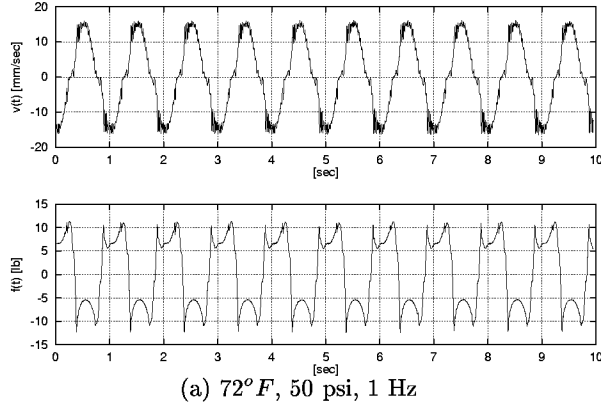


Figure 4: The velocity $v(t)$ and friction signal $f(t)$ at $72^{\circ}F$, 50 psi, and 1 Hz, and $130^{\circ}F$, 50 psi, and 1 Hz.

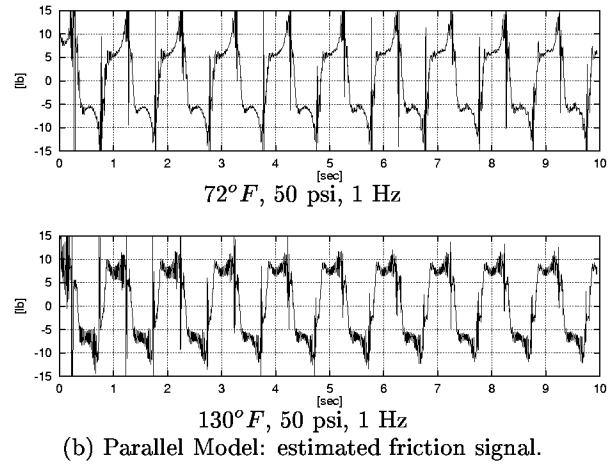
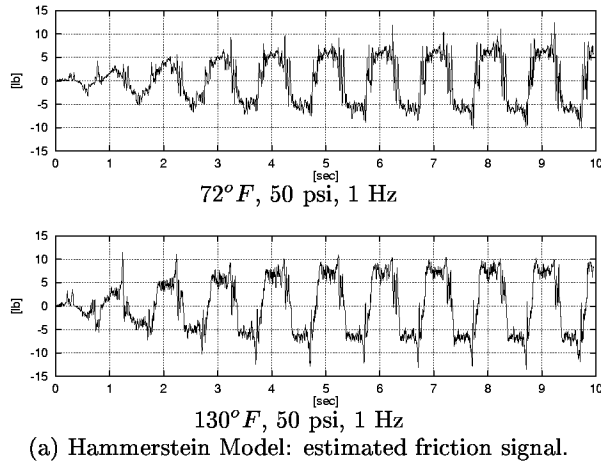


Figure 5: Simulation results of Hammerstein Type Models.

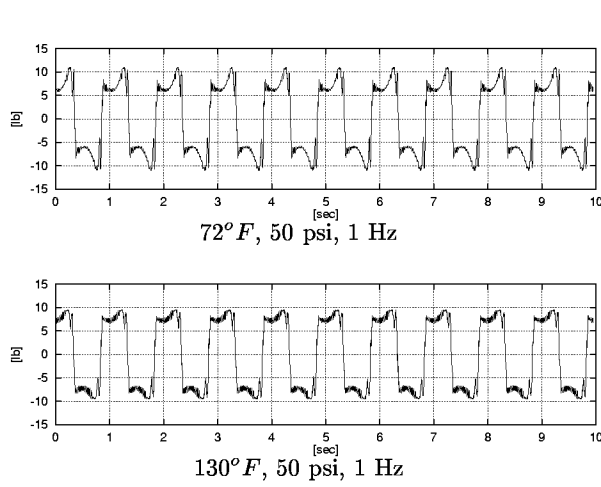


Figure 6: Simulation results of finite-state memory model: Estimated friction signals.

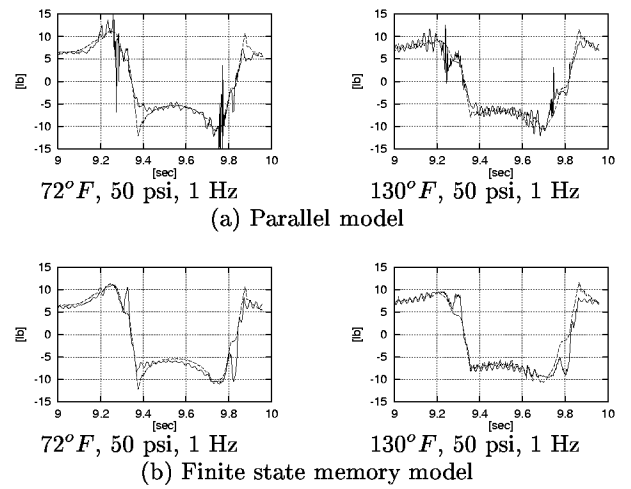


Figure 7: Detailed plots of the friction signals and estimated friction signals. Solid line: the estimated friction signal. Dashed line: the actual friction signal.