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Parameter Design of an Hydraulic Track Motor System

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ABSTRACT

This paper presents the parameter design method for the desired time response of hydraulic track motor system of an industrial excavator. The dynamic response depends upon many component parameters such as motor displacement, spring constant, and various valve coefficients. Most of them are to be determined to obtain the desired response while some parameters are fixed, or discrete for the off-the-shelf type components.

The parameters might be selected through repeated simulations of the system once the system is mathematically represented. This paper, however, presents optimization technique to select two parameters using a parameter optimization technique. The variational approach is applied to the system equations which are represented as state equations and from those system equations derived are the adjoint equations. The gradients for each parameter also are formed for the iterations.

1. INTRODUCTION

The hydraulic track motor system is a travelling unit of an excavating vehicle and it also keeps the vehicle from overunning. The system consists mainly of several components such as hydraulic motor, main control valves(M. C. V), and the counter balance valves(C. B. V). Figure 1. shows the hydraulic circuit diagram of the system. The main control valve steered by the operator controls the flow and directions to the motor. The spool in the conter balance valve moves very fast depending upon the pressure built in the hydraulic line from the motor to M. C. V. and has a function of preventing the motor from overunning by blocking flow to the valve effectively.

Many design parameters in these components govern the dynamic response of the system. Desired dynamic response may be possibly obtained by the use of repeated simulations. Such a method, however, does not give good results and is not efficient for comparatively large systems. Therefore, an optimization method has been seeked to select the design parameters effectively.

This paper presents a numerical optimization scheme for the desired time response of a particular state variable which shows rapid changes with high natural frequency. The variational approach was applied to derive the gradients of the performance index which is the difference between the desired response and predicted one for the state variable.

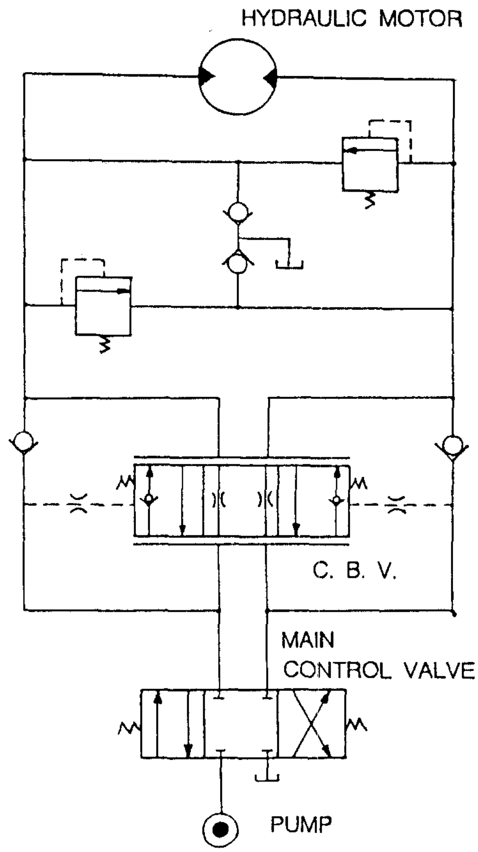

Fig. 1 Hydraulic Circuit Diagram

2. PARAMETER DESIGN

2.1 System Modeling

Modeling is first needed to form the system equations of the track motor system. Multiport component concepts are used to model the system as easily considered for an hydraulic system. The block diagram can be obtained easily by using the multiport concept.

The system behavior can be simply described as follows,
the hydraulic fluid flows through the M. C. V. to one side of the track motor to start the motion. A remote control valve is used to reduce the operating force of the M. C. V. The valve characteristics makes following linearized flow equations :

$$Q_1 = u_1 - k_1 P_1 \qquad (2.1)$$

$$Q_2 = k_2 P_2 \qquad (2.2)$$

$$Q_3 = k_3 P_6 + k_4 (P_3 - P_2) \qquad (2.3)$$

where Q's are the flow rates, k's are the valve coefficients, u_1 is the input to the system, P_1 is the pressure in the line from the M. C. V. to the track motor, P_2 is the pressure in the line from the C. B. V. to the M. C. V., P_3 is in the line from the track motor to C. B. V., and P_6 is the pressure acting to the right side of C. B. V.

The above equations can be written as state equations if the Implicit Method is applied. That is, the equations can be rewritten if both sides of the equations are differentiated with respect to time.

Applying continuity to each fluid volume depicted in Figure. 1 gives following equations,

Volume from M. C. V. to motor :

$$\dot{P}_1 = \frac{\beta}{V_2}[Q_1 - k_f (P_1 - P_4) - D_T N_T] \qquad (2.4)$$

Volume from C. B. V. to M. C. V. :

$$\dot{P}_2 = \frac{\beta}{V_5}[(Q_3 - Q_2) + k_f (P_2 - P_3)] \qquad (2.5)$$

Volume from motor to C. B. V. :

$$\dot{P}_3 = \frac{\beta}{V_3}(D_T N_T - Q_3) \qquad (2.6)$$

Volume in left side of C. B. V. :

$$\dot{P}_4 = \frac{\beta}{V_{1r}}[k_f (P_1 - P_4) - A_s v_s] \qquad (2.7)$$

Volume in right side of C. B. V. :

$$\dot{P}_5 = \frac{\beta}{V_{4r}}[-k_f (P_1 - P_4) + A_s v_s] \qquad (2.8)$$

where β is the bulk modulus of the fluid, V's are the volume involved, D_T is the motor displacement, N_T is the speed of motor, A_s is the area of the spool of C. B. V., k_f is its valve coefficient, and v_s is the speed of the spool.

Equation of motion of the spool of C. B. V. is written as

$$\dot{v}_s = -\frac{K_s}{M_s}x_s + \frac{A_s}{M_s}(P_4 - P_5) \qquad (2.9)$$

where K_s is the spring constant of the spring in both sides of the spool, M_s is the mass of the spool, and x_s is the displacement of the spool.

Equation of rotary motion for the rotating parts of the track motor is also written as

$$\dot{N}_T = \frac{1}{J_T}[D_T(P_1 - P_3) - C_D D_T \mu N_T - C_f D_T (P_1 - P_3)] \qquad (2.10)$$

where N_T is the rotating speed of the motor, J_T is the mass moment of inertia of rotating parts, C_D is the drag coefficient of the motor, μ is the viscosity of the fluid, and C_f is the friction coefficient of the motor.

Also, definitions relating the speed and displacement of the spool and the motor are written as

$$\dot{x}_s = v_s \qquad (2.11)$$

$$\dot{\theta}_T = N_T \qquad (2.12)$$

respectively, where θ_T is the angular displacement of the motor.

The parameters such as D_T, K_s, M_s, A_s, and other design parameters govern the system characteristics. However, how much they givern the system should be investigated.

2.2 Variational Approach

The above equations derived so far form a set of state equations and can be represented as

$$F_i = \dot{x}_i - A_i(x_i, p_j), \qquad i = 1,2,\cdots,9 \qquad (2.13)$$

where x's are the state variables, F's have zero value, and p's are the parameters to be selected.

It is noticed that x and y are the functions of p. Once a desired time response is defined mathematically, the objective functional can be written as

$$I(p) = \int_0^t f(x_i, p_j)dt \qquad (2.14)$$

where $f(x_i, p_j) = |x_{des} - x_1|$ because the goal is to minimize the error between the desired reponse $x_{des}$and the predicted reponse x_1 over an interested time interval. The state variable x_1 means the pressure P_1 acting in the line from M. C. V. to the motor.

By perturbing the variables, derivative-like conditions can be derived for each variable. Perturbed variables $\overline{x_i}$, $\overline{p_j}$ can be defined as

$$\overline{x_i} = \overline{x_i}(\overline{p_j}), \qquad i = 1,2,\cdots,9 \qquad (2.15)$$

$$\overline{p_j} = p_j + \varepsilon_{pj}\gamma_{pj}, \qquad i = 1,2 \qquad (2.16)$$

where p_j is a certain parameter that can minimize the functional I, the value of ε_{pj} is a small scalar, and γ_{pj} is a function with continuous second derivatives.

An augmented integral is formed by taking into account Equation (2.13) as constraints, i.e.,

$$I(p) = \int_0^t [\, f(x_i, p_j) + \sum_{i=1}^{9}\lambda_i F_i \,]\, dt \qquad (2.17)$$

where λ_i is the Lagrangian multiplier for the constraint equations. Since the integrand of Equation (2.17) is dependent on the function x_i and p_j, the the necessary conditions for an optimum can be obtained by setting the derivatives of the functional $I(p)$ zero with respect to each ε:

$$\frac{dI(p)}{d\varepsilon} = \frac{\partial f}{\partial p_j} + \sum_{k=1}^{9} \lambda_k \frac{\partial F_k}{\partial p_j} \tag{2.18}$$

Reducing the above equation yields to the following equations :

$$\frac{\partial f}{\partial x_i} + \sum_{k=1}^{9} \lambda_k \frac{\partial F_k}{\partial x_i} - \frac{d\lambda_i}{dt} = 0 \tag{2.19}$$

$$\frac{\partial f}{\partial p_j} + \sum_{k=1}^{9} \lambda_k \frac{\partial F_k}{\partial p_j} = 0 \tag{2.20}$$

Equation (2.19) can be rewritten as

$$\frac{d\lambda_i}{dt} = \frac{\partial f}{\partial x_i} + \sum_{k=1}^{9} \lambda_k \frac{\partial F_k}{\partial x_i} \tag{2.21}$$

which are called adjoint equations and can be solved by numerical integrations. Equation (2.20), however, is used for the gradient evaluation.

2.3 Adjoint Equations

Applying the approach discussed so far to Equations (2.4) through (2.12) yields following adjoint equations:

$$\dot{\lambda}_1 = d_1 + \lambda_1 \frac{\beta}{V_2}(-k_1 - k_f) - \lambda_4 \frac{\beta}{V_{1r}} k_f - \lambda_8 \frac{1}{J_T} D_T(1 - C_f)$$

$$\text{where} \quad d_1 = \begin{cases} 1 & \text{for } x_1 \geq x_{des} \\ -1 & \text{for } x_1 < x_{des} \end{cases} \tag{2.22}$$

$$\dot{\lambda}_2 = \lambda_2 \frac{\beta}{V_5}(k_4 + k_2 - k_f) - \lambda_3 \frac{\beta}{V_3} k_4 - \lambda_5 \frac{\beta}{V_{4r}} k_f \tag{2.23}$$

$$\dot{\lambda}_3 = \lambda_2 \frac{\beta}{V_5}(-k_4) + \lambda_3 \frac{\beta}{V_3} k_4 + \lambda_8 \frac{1}{J_T} D_T(1 - C_f) \tag{2.24}$$

$$\dot{\lambda}_4 = -\lambda_1 \frac{\beta}{V_2} k_4 + \lambda_4 \frac{\beta}{V_{1r}} k_4 - \lambda_7 \frac{A_s}{M_s} \tag{2.25}$$

$$\dot{\lambda}_5 = \lambda_2 \frac{\beta}{V_5} k_4 + \lambda_5 \frac{\beta}{V_{4r}} k_4 - \lambda_7 \frac{A_s}{M_s} \tag{2.26}$$

$$\dot{\lambda}_6 = -\lambda_2 \frac{\beta}{V_{U5}} k_3 + \lambda_3 \frac{\beta}{V_3} k_3 + \lambda_7 \frac{K_s}{M_s} \tag{2.27}$$

$$\dot{\lambda}_7 = \lambda_4 \frac{\beta}{V_{1r}} A_s - \lambda_5 \frac{\beta}{V_{4r}} A_s - \lambda_6 \tag{2.28}$$

$$\dot{\lambda}_8 = \lambda_1 \frac{\beta}{V_2} D_T - \lambda_3 \frac{\beta}{V_3} D_T + \lambda_8 \frac{1}{J_T} C_d D_T \mu - \lambda_9 \tag{2.29}$$

$$\dot{\lambda}_9 = 0 \tag{2.30}$$

Also the left hand side of Equation (2.20) can be rewritten as gradients,

$$\frac{\partial I(p)}{\partial p_j} = \frac{\partial f}{\partial p_j} + \sum_{k=1}^{9} \lambda_k \frac{\partial F_k}{\partial p_j} \tag{2.31}$$

Equation (2.31) describe the change of the objective functional as the parameters change in an iterative manner. Evaluation of (2.31) gives the direction of optimization for each parameter. A steepest descent method can be applied to improve convergence.

The optimization algorithm can be described as follows,

(1) Choose the parameters to be selected.
(2) Initilize the parameter values with feasible values.
(3) Solve for the state variables using the state equations.
(4) Solve for the Lagrangian multipliers using the adjoint equations.
(5) Evaluate the gradients using Equation (2.31).
(6) Evaluate the next value of parameters using the steepest descent method,

$$p_{i+1} = p_i + \frac{\partial I}{\partial p_j}. \tag{2.32}$$

(7) Check to see if the parameters converge.
(8) Repeat the steps (3) through (7) if not converged.

The optimization procedure is shown in Figure 2.

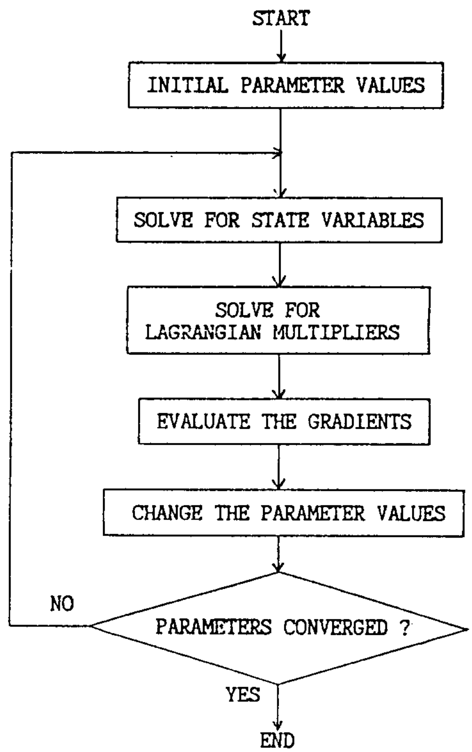

Fig. 2 Optimization Procedure

Two distinctive parameters are chosen for the design and they are motor displacement and spring constant. They are defined p_1 and p_2, respectively. Equation (2.31) can then be written as

$$\frac{\partial I}{\partial p_1} = \lambda_1 \frac{\beta}{V_2} N_T + \lambda_3 \frac{\beta}{V_3} N_T + \lambda_8 \frac{1}{J_T} [(1 - C_f)(P_1 - P_4) - C_d \mu N_T] \qquad (2.33)$$

$$\frac{\partial I}{\partial p_2} = - \lambda_7 \frac{1}{K_s} x_s \qquad (2.34)$$

As discussed earlier, the state equations should be solved first before solving the adjoint equations since Equations (2.33) and (2.34) contain state variables.

3. RESULTS AND CONCLUSIONS

3.1 Results

The desired time response of P_1 was given as a very fast and high damped system response. Initial values for two parameters to be optimized were given 5 m^3/rad, 80 N/m respectively. They are of course far from the optimal values. Other fundamental parameters were given fixed as follows,

$$\beta = 1.16\times10^8 \quad Kg/m^2 \qquad (3.1)$$

$$C_d = 1\times10^5 \quad (dimensionless) \qquad (3.2)$$

$$C_f = 0.2 \quad (dimensionless) \qquad (3.3)$$

$$A_s = 3.14\times10^{-4} \quad m^2 \qquad (3.4)$$

$$M_s = 0.2 \quad Kg \qquad (3.5)$$

$$J_T = 30 \quad Kg \cdot m^2 \qquad (3.6)$$

The input to the system was assumed as a step input. Ringe-Kutta 4th order was used for the integrations both for the state and the adjoint equations.

By repeating the procedure mentioned in the previous section, it was obtained that the predicted response converged to the desired response even though the initial set of parameters was far from the optimal values. Figure 3. shows the results. It shows that the optimization enables the reponse move to the desired response.

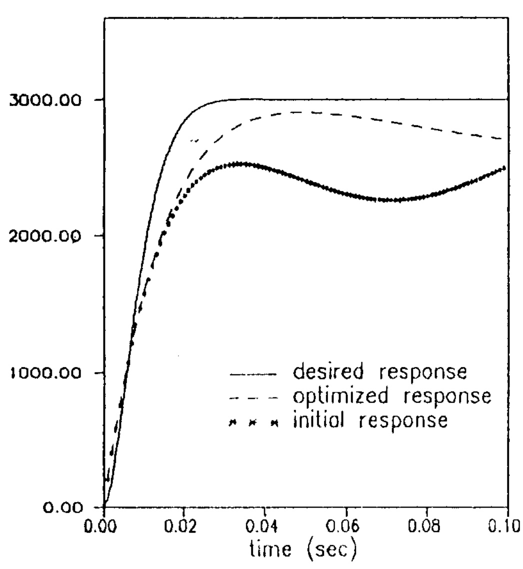

Fig. 3 Time Reponses

3.2 Concluding Remarks

The optimization technique is applied to an hydraulic track motor system and the results shows satisfactory convergence. It saves calculation time compared to the repeated simulations. The use of conjugate gradient method might be able to improve the speed of convergence.

This optimization method can be applied to other dynamic systems where the systems are represented as state equations. It also can be used as a design tool since less simluations are required.

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