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A Design Method of Fuel Pump System Using Adaptive Control

(適應制御를 利用한 燃料펌프 시스템의 設計方法)

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要 約

Weighted Least Square(W. L. S.)알고리즘을 통한 係數識別 理論과 出力 誤差를 最小로 하기위해 한단계 앞서서 制御入力을 決定하는 制御理論을 結合한 基準 모델 適應制御를 應用한 燃料펌프 시스템을 設計하였다.

시스템의 性能에 關係되는 샘플링 週期 T, 比重係數 λ 및 State Variable Filter(S. V. F.)의 필터係數 f의 값은 컴퓨터 시뮬레이션을 통해 決定했으며, 특히 周圍溫度의 變化로 인해 燃料의 粘性度가 변하므로서 工程의 動特性을 나타내는 工程係數가 변하는 것에 대한 制御시스템의 適應度를 레귤레이션(regulation)과 追從(tracking) 觀點에서 考察하였다.

Abstract

The fuel pump system is developed with the Model Reference Adaptive Control (M.R.A.C.) algorithm based on the Weight Least Square (W.L.S.) algorithm for the parameter identification and the one step ahead dead-beat control with the reference model.

The value of some parameters as the sampling period T, the weighting coefficient λ, and the State Variable Filter (S.V.F.) coefficient f which affects the system performance are selected through computer simulation.

For the variation of the plant dynamics especially due to the change of the fuel viscosity with the ambient temperature condition, the adaptability of the control system is studied in the case of regulation and tracking.

I. Introduction

The successful design of a good control system is dependent to a large extent on the availability of the parameter values describing the dynamic characteristics of a plant. In most cases the plant parameters and disturbances are unknown or change with time. In these cases the adaptive control system has been seen as a good control system for good performance. The plant parameters will be identified by measuring the input and output of the plant and the control parameters can be developed with the identified plant parameters.

In the adaptive control system the para-

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meter identification is the most important part and numerous studies have been done in this field. In the beginning the stability of the control system was emphasized and many studies were based on the Lyapunov's direct method[1-6], and on the Popov's hyperstability theorem.[7-9] Some efforts for improving the convergence time of the parameter identification were made by Kreisselmeier[11] in the continuous time domain and by Suzuki[12] in the discrete time domain. Suzuki developed the Weighted Least Square (W.L.S.) algorithm where the performance index was the sum of the squared output error weighted exponentially. The performance of this algorithm was verified through some applications such as the speed control system of D.C. motor[13].

In this paper, the fuel pump control system is developed with the basis of the Model Reference Adaptive Control (M.R.A.C.) system where the plant parameters are identified with W.L.S. algorithm and the control law is applied so that the output of a plant can follow that of a reference model. The fuel pump system developed in this paper is used in a turbojet engine for a small vehicle. And JP-4, aviation fuel, is used for this fuel pump system.

This paper represents the effects of selected parameters' variation on the performance of the control system; the sampling period T, the weighting coefficient of the W.L.S. algorithm λ, and the state variable filter (S.V.F.) coefficient f. Through the computer simulation the proper values can be determined for good performance. The computer simulation is also performed for the analysis of the adaptability of the control system in the regulation and tracking under the time-varing fuel viscosity due to the variation of the ambient temperature.

II. Model Referenced Adaptive Control

1. Weighted Least Square (W.L.S.) Algorithm

The state equation of a discrete single input single output (SISO) plant can be expressed as

$$\underline{x}(K+1)=A\underline{x}(k)+b\underline{u}(k);\ \underline{x}(0)=\underline{x}_o$$
$$y(k)=\underline{c}^T\underline{x}(k) \qquad (1)$$

where $\underline{x}(k)$ is n-order state vector, u(k) and y(k) are the input and the output of the plant respectively. If the plant is supposed to be observable the above equation can be written as the following canonical form.

$$A=\left[\begin{array}{c|c} \underline{a} & I_{n-1} \\ \hline & 0 \end{array}\right] \quad \begin{array}{l} \underline{a}=(a_1, a_2, \ldots\ldots a_n)^T \\ \underline{b}=(b_1, b_2, \ldots\ldots b_n)^T \\ \underline{c}=(1, 0, \ldots\ldots 0)^T \end{array} \qquad (2)$$

To use the concept of the state variable filter (S.V.F.) which was introduced by Rucker[14] and has been applied by some others[1], [10,15,16], we define ϕ_1 and ϕ_2 as the state vectors of the filters whose input is the output and the input of the plant respectively as in Fig 1. The state equation is as follows.

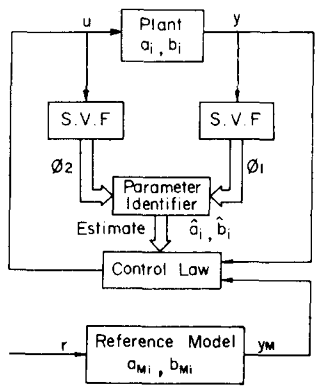

Fig. 1. Schematic diagram of M.R.A.C.

$$\underline{\phi}_1(k+1)=F\underline{\phi}_1(k)+\underline{c}y(k) \qquad (3)$$
$$\underline{\phi}_2(k) \quad =F\underline{\phi}_2(k)+\underline{c}u(k) \qquad (4)$$

where

$$F=\left[\begin{array}{c|c} \multicolumn{2}{c}{\underline{f}} \\ \hline I_{n-1} & 0 \end{array}\right] \quad \underline{f}=(f_1, f_2, \ldots\ldots f_n) \qquad (5)$$

and F is the stable matrix. The filter coefficient fi can be determined by the designer for the stability of the control system.

Now the new vector p and o can be defined as

$$\underline{p}=(\underline{p_1}^T, \underline{p_2}^T) \qquad (6)$$
$$\underline{\phi}=(\underline{\phi_1}^T, \underline{\phi_2}^T)$$

where

$$\underline{p}_1 = \underline{a} - \underline{f} \qquad (7)$$
$$\underline{p}_2 = \underline{b}$$

Note that in the above form the unknown parameters are contained in the vectors $\underline{p}_i$ (i= 1,2).

Using a performance index which is defined as the sum of the squared output error weighted by the weighting coefficient ($0 < \lambda < 1$), the estimates p(k) which minimize the perfor mance index is given by the recursive equation

$$\hat{\underline{p}}(k+1)=\hat{\underline{p}}(k)+l(k+1)[z(K+1)-\underline{\phi}(k+1)^T\hat{\underline{p}}(k)] \qquad (8)$$

where

$$\underline{l}(k+1)=\frac{\frac{T(\lambda, k)}{\lambda^2}}{1+\underline{\phi}(k+1)^T\frac{T(\lambda,k)}{\lambda^2}\underline{\phi}(k+1)} \qquad (9)$$

and

$$T(\lambda,k+1)=\frac{T(\lambda,k)}{\lambda^2}-\frac{\frac{T(\lambda,k)}{\lambda^2}\phi(k+1)\,\phi(k+1)^T\frac{T(\lambda,k)}{\lambda^2}}{1+\phi(k+1)^T\frac{T(\lambda,k)}{\lambda^2}\phi(k+1)} \qquad (10)$$

where $\underline{l}(k)$ and $T(\lambda, k)$ are n th - order vector and 2n x k matrix respectively which are used for convenience. z(k) can be expressed as

$$z(k) = y(k) - \underline{c}^T F^K \underline{x}_o \qquad (11)$$

Note that if $\underline{x}_o = 0$, then z(k) = y(k).
The above equations can be easily derived in the same way as shown by Suzuki.[12] Equation (10) is not applicable until k=2n, because $T(\lambda, k)$ cannot be defined for $k < 2n$. However, if the initial value of $T(\lambda, k)$ is set as

$$T(\lambda,0) = d^2 I_{2n} \quad ; d \gg 1 \qquad (12)$$

equation (10) can be applicable for all k. [12]

2. Model Following Control Law

Equation (1) and (2) can be rewritten as the difference equations such as

$$y(k+1)=\sum_{i=1}^{n} a_i y(k-i+1)+\sum_{i=1}^{n} b_i u(k-i+1) \qquad (13)$$

Corresponding to this equation, we consider the reference model described by

$$y_M(k+1) = \sum_{i=1}^{n} a_{Mi} y(k-i+1)+\sum_{i=1}^{n} b_{Mi} r(k-i+1) \qquad (14)$$

where $y_M(k)$ is the output of the model, r(k) is the reference input (assummed to be bounded), and a_{Mi} and b_{Mi} (i=1, 2, ... n) are the constant parameters to be specified such that the reference model yields a stable and desired response to the input r(k). The purpose considered here is to synthesize the control input u(k) so that the plant output y(k) follows the model output y_M (k), using the plant parameter estimates obtained from the adaptive identifier.

Now a new performance index J(k) can be defined as

$$J_1(k+1)=1/2[y_M(k+1)-y(k+1)]^2 \qquad (15)$$

Substituting (13) into (15) and minimizing J(k) with respect to u(k) yields

$$u(k)=1/b_1 [y_M(k+1)-\sum_{i=1}^{n} a_i u(k-i+1) - \sum_{i=1}^{n} b_i u(k-i+1)] \qquad (16)$$

However, such a u(k) cannot be determined because the plant parameters are unknown. Thus we must synthesize u(k) adaptively by using the estimates a_i (k) and b_i (k) as follows:

$$u(k)=1/\hat{b}_1(k)[y_M(k+1)-\sum_{i=1}^{n}\hat{a}_i(k)y(k-i+1) - \sum_{i=2}^{n}\hat{b}_i(k)u(k-i+1)] \qquad (17)$$

III. Computer Simulation

1. The Plant Dynamics

The fuel pump system is composed of a D.C. motor and a gear type pump. The D.C. motor is a permanent magnet type and its rated voltage and current is 28V-DC and 25A. The maximum rotational speed of the motor is 9,000 rpm.

Now let the applied input voltage and rotational speed be V and N respectively. The transfer function of the D.C. motor is usually expressed by a 2nd-order equation. But in our pump system the armature inductance (La=0.8uH) is relatively small and the viscosity coefficient of the fuel must not be neglected. Hence the transfer function of the rotational speed over the input voltage [N(s)/V(s)] for the motor can be expressed as

$$\frac{N(s)}{V(s)} = \frac{A}{1+\tau S} \qquad (18)$$

where A and τ can be written as follows

$$A = \frac{K_t}{K_t K_e + R_a B}$$

$$\tau = \frac{R_a J}{K_t K_e + R_a B} \qquad (19)$$

where Kt is the torque constant, Ke is the counter electromotive force (CEMF) constant, Ra is the armature resistance, J is the moment of inertia, and B is the viscosity of the fuel. The parameter values used in the computer simulation are as follows

$Kt = 2.87 \times 10^5$ [dyne. cm/amp]
$Ke = 2.87 \times 10^{-2}$ [volt/rad-sec]
Ra = 0.5 [ohms]
J = 50 [g-cm^2]
B = 4.8 [dyne-cm-sec] (20)

The quantity of the fuel supplied by a gear type pump is proportional to the rotational speed of the pump and the transfer function can be simply written as [17]

$$G(s)/N(s) = Cp \qquad (21)$$

where G(s) is the fuel quantity supplied, N(s) is the rotational speed, and Cp is a contant.

2. Application to the Plant

Now let the applied voltage and the supplied fuel quantity be u(k) and y(k) respecticely. From equation (21) and (18) the difference equation can be easily derived as [18],

$$y(k+1)=ay(k)+bu(k) \qquad (22)$$

where

$$a=e^{-T}/\tau,\ b=Acp\,(1-e^{-T}/\tau) \qquad (23)$$

where T is the sampling period.
S.V.F. is expressed as

$$\phi_1(k+1)=f\phi_1(k)+y(k)\ ;\ \phi_1(0)=0 \qquad (24)$$
$$\phi_2(k+1)=f\phi_2(k)+u(k)\ ;\ \phi_2(0)=0 \qquad (25)$$

Setting $\hat{x}_o = 0$ yields z(k)=y(k) from equation (11). And if we let d^2=100 for (12), the parameter estimates $\hat{\underline{p}}(k)$ can be obtained from equation (8), (9), and (10). Using the estimates $\hat{\underline{p}}(k)$ and equation (6), $\hat{a}(k)$ and $\hat{b}(k)$ can also be easily obtained. Now let the reference model as

$$y_M(k+1)=b_M r(k) \qquad (26)$$

where b_M=12.5 and $0 \leqslant r(k) \leqslant 6$. Note that the reference model is designed so that the pump system can supply the fuel at the rate of 12.5 cm^3/sec per 1 volt of input voltage with the maximum fuel rate of 75 cm^3/sec, and so that the output of the plant follows the reference input with one step delay. Using equation (17) for the control law yields

$$u(k)=1/\hat{b}(k)\,[y_M(k+1)-\hat{a}(k)y(k)] \qquad (27)$$

3. Simulation

The parameters which affect the dynamic characteristics of the plant are A, τ and Cp. The variation of the fuel viscosity B due to the change of the ambient temperature will change the value of A and τ as in equation (19). We assume that the fuel pump system is used for supplying JP-4 aviation fuel to the turbojet engine and that the vehicle whose propulsion is provided by the turbojet engine makes a flight with altitude of sea-level to 35,000ft. The standard atmospheric temperature is about 59°F at sea-level and about -65.8°F at 35,000ft altitude.[17] With the temperature variation as above, the aviation fuel JP-4 has the characteristics of the viscosity coefficient change from B=1.36 [dyne-cm-sec] at 59°F to B=8.0 [dyne-cm-sec] at -65.8°F.[20] Cp can also vary with the variation of the pressure at the output of the pump. τ is the time constant of the plant, and A and Cp affect the steady state gain. The computer simulations were carried out for the case where the time constant and the gain varied by changing B in a step-like manner, and where they are constant. The consecutive runs were made for the various values of the sampling period T, for those of the weighting coefficient λ, and for those of the state variable filter coefficient f; for the cases of T=1ms, 2ms, 4ms and 10ms, of λ=1.0, 0.8 and 0.5 and of f=0.0, 0.5 and 0.7. And also the simulations were carried out for the two cases where the reference input r(k) was constant for the analysis of the regulation error, and where the reference input r(k) varies sinusoidally for that of the tracking error. The simulation was obtained using cyber 170/740.

4. Results and Discussion

Through the computer simulation, the transient responses of the plant output y(k), the output error y_M(k)-y(k) and the parameter estimates $\hat{a}$(k) and $\hat{b}$(k) for the constant input and the sinusoidal input are investigated. Typical results for each input are shown in Fig. 2 and Fig. 3 respectively for the sampling period T=1ms, the weighting coefficient λ=0.8 and the S.V.F. filter coefficient f=0.5 At k=50, the

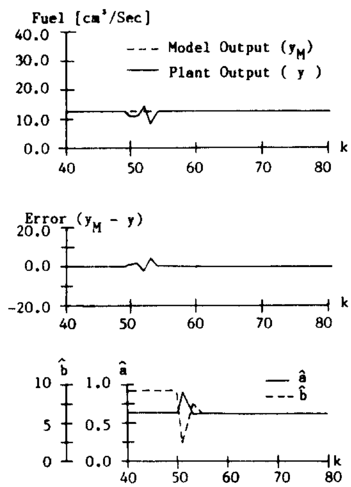

Fig. 2. Result for r(k)=U(9k-10) (T=1ms, λ=0.8, f=0.5).

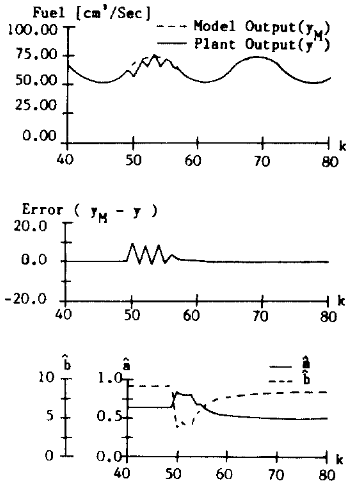

Fig. 3. Result for r(k)=5+sin(2 k/16) (T=1ms, λ=0.8, f=0.5).

viscosity coefficient, B is increased by 3 times of the previous value in a step-like manner, and the transient characteristics of the adaptation of the plant output to the model output are observed.

Note that the main purpose of the simulation is to decide the proper values of the sampling period T, the weighting coefficient λ and the S.V.F. coefficient f, so that the output error y_M(k)-y(k) is small and the convergence time is short as possible. Hence we carry the simulation for the cases of T=1ms, 2ms, 4ms and 10ms, of λ=1.0, 0.8 and 0.5, and of f=0.0, 0.5 and 0.7. Now we define a performance index to select the proper value of the parameters such as

$$J = \frac{1}{N}\sum_{k=1}^{n}[y(k) - y(k)] \quad (28)$$

where J_2 is the performance index defined as the time averaged sum of the squared output error. And n is the number of the discrete time intervals for calculating the performance index. The value of n can be selected so that all of the non-zero output error should be included into the performance index. In this paper n=50 is used.

To decide the proper value of the parameters, we change the value of one of the three parameters (T, λ, and f) with the change of the viscosity coefficient, B, in a step-like manner, and investigate the performance index defined in equation (28) and the convergence time.

The performance index and the convergence time for variation of the sampling period(T) are obtained through the computer simulation and shown in Fig. 4. As shown in this figure two kinds of input, constant and sinusoidal, are applied to the control system for studying a regulation and a tracking problem respectiviely. From a point of the performance index, it is larger as the sampling period increases as shown in Fig. 4. Hence the performance of the control system for the short sampling period is better than that for the long one. Especially for the sinusoidal input with T larger than about 2.0ms, the performance index increases abruptly. Considering the plant time constant τ=1.5ms, it can be said that T should be smaller than the plant time constant for better performance. And the convergence time for the output error to go nearly null is also shown in Fig. 4. The output of the plant converges rapidly to the that of the model for the small value of T. Even if it can be easily understood that the smaller the sampling period, the better the performance of the control system, it must be also considered that in the case of realizing the actual pump system, the sampling period T is limited by the number of instructions performed during a period and processor clock time.

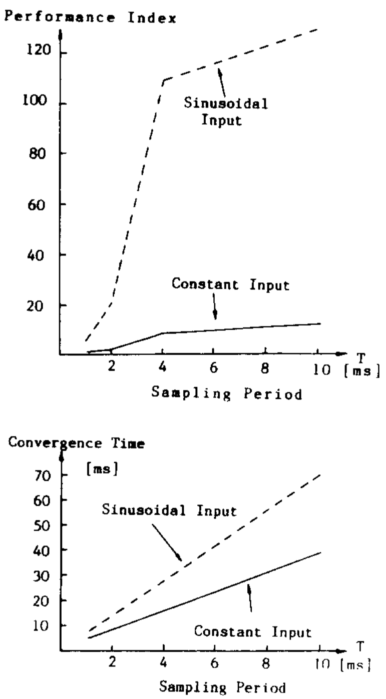

Fig. 4. Results for Variation of the Sampling Period, T (λ0.8, f=0.5).

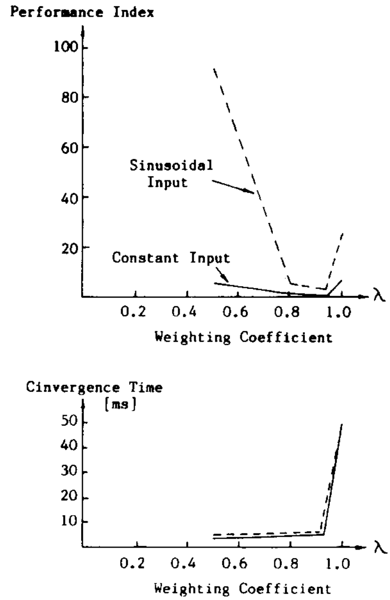

Fig. 5. Results for Variation of the Weighting Coefficient, λ (T=1ms, f=0.5).

Fig. 5 is the result for the weighting coefficient λ=0.5, to 1.0. for the of λ=1.0, the output of the plant takes a long time for convergence to that of the reference model in both cases of the constant and the sinusoidal input. This is due to the fact that when λ=1.0, all output error data are evaluated with the same weight and hence new data are swamped by past data. If we consider the value of λ smaller than 1.0, the convergence time decreases but the performance index increases as λ decreases as shown in Fig.5. Note that W.L.S. algorithm with $0.5<\lambda<1.0$ is applicable for those cases where the plant parameters vary with time, and hence it is useful for an adaptive control system if we decide the value of λ properly.

Also the result of computer simulation for varing the S.V.F. filter coefficient f=0.0 to f=0.7 is shown in Fig.6. The result tells us that,

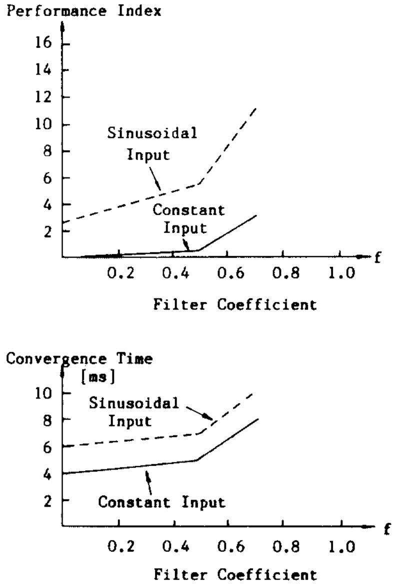

Fig. 6. Results for Variation of the Filter Coefficient, f(T=1ms, λ=0.8).

for the case of the plant whose input and output data are noiseless, the smaller the performance index and the convergence time the smaller the filter coefficient, f. A designer can determine its proper value for the stability and the performance of the control system in a noisy condition.

From Fig.4,5 and 6, we can select the proper values of parameters for the small output error and the short convergence time such as T=1ms, λ=0.8, f=0.5. The simulation result with these parameter values are shown in Fig.2 and Fig.3 for the constant input and the sinusoidal input respectively. It is easily seen that the plant output converges rapidly to the model output with relatively small error even when the plant parameters vary with time in a step like manner.

IV. Conclusion

A model referenced adaptive controller for the fuel pump has been developed. The proper values of the sampling period, weighting coefficient and the state variable filter parameter which affect the performance of the control system can be selected through computer simulation. The simulation results have been discussed for various values of parameters. The weighting coefficient and the S.V.F. filter coefficient f are suggested to be dermined by taking measurement noise into consideration. The proposed model reference adaptive control system based on the exponentially weighted least-square method yields a good application to the fuel pump system and it is easy to implement.

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