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OPTIMAL REGULATOR APPLIED TO ROTARY SHEARING SYSTEM

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ABSTRUCT: The design and application of optimal control technique to the rotary shearing system is mentioned in this paper.

To maximize the accuracy in both shearing length and blade speed at shearing, time-varying gain patterns for closed loop control are designed on the basis of fixed terminal time constrained optimal regulator.

The performance accuracy in real application has greately improved than the conventional way of shearing control

KEYWORDS: Rotary cutter; Flying crop shearer; Closed loop optimal control; Time-varying feed back control gains.

INTRODUCTION:

Rotary shearer is the apparatus shearing the aimed points on object at its running speed in various industry fields as steel rolling plant and paper manufacturing process.

In this shearing process accurate cutting length control must be achieved and the shearer speed must coincide exactly with the motion of the object at the cutting instance.

The speed of line operation will suffer frequent fluctuation especially in the operation stage just after the start-up and prior to shutdown. To realize accurate cut point control while following up the fluctuation in speed of line operation, feedback regulation of shear drive motor is thought most appropriate.

The closed loop realization of this optimalized shearing control works sufficiently robust for the uncertainties in the object dynamics and unavoidable changes in system parameters.

DISCRETIZED SYSTEM EQUATION OF THE MODEL:

The mechanism of rotary shearer is shown in Fig.1, a pair of blades are inlaid on the drums each rotates diversely on the fixed axis.The drum is connected to the speed regulated electrial drive system.

The outlie of optimal shearing control is shown in Fig.2.

The motion of the object to be sheared is measured with the contact rolls, the velocity V_b and the point length to be sheared L_b are shown in Fig.2.

When scaling the position of the blade in its circumference direction L_s and the speed of blade V_s, the control problem is formulated as follows.

Assuming the dynamics of the drive motor is linear and a first order lag with cutoff frequency w, we can get the discrete system equations of the shearer with sampling interval T;

$$x=(L_s,V_s)^t \tag{1}$$

$$x(k+1)=\phi(T)x(k)+h(T)u(k) \tag{2}$$

where t denotes for transposition and k for sampling period,

$$\phi(T)=\begin{bmatrix} 1.0 & (1.0-e^{-wT})/w \\ 0 & e^{-wT} \end{bmatrix} \tag{3}$$

$$h(T)=\begin{bmatrix} (wT-1.0+e^{-wT})/w \\ 1.0-e^{-wT} \end{bmatrix} \tag{4}$$

u(k) is for the reference signal to the speed regulator of the drive motor at sampling period k.

The motion of the object is represented by the vector y

$$y=(L_b,V_b)^t \tag{5}$$

The control problem of this rotary shear is to generate the optimal sequence of control signal [u(k)] knowing the state [L_b, V_b, L_s, V_s].

For the sake of convenience in implementing into a digital control processor, we formalize the system equation in discrete time form.

Defining the error vector e(k) between the shear motion x(k) and the object y(k).

$$e(k)=y(k)-x(k) \tag{6}$$

We can evaluate the performance of control law in the following time-weighted guadratic form of the above mentioned error e(k).

$$I_N=\sum_{k=1}^{N}[e^t(k)Q(k)e(k)+u^2(k-1)] \tag{7}$$

The dynamics of the error state e(k) is also expressed in the same form as in eqn.(2)-(4).

$$e(k+1)=\phi(T)e(k)+h(T)u(k) \tag{8}$$

The shearing control is to find the optimal solution for eqn(8), that momirize the time weighted squared errors in eqn(7).

OPTIMAL GAIN PATTERN SYNTHESIS:

Q(k) is arbitary weights on the error state at sampling k, which should be sellected any value at least positive defenite, in the special case of this rotary shearing system, the state errors only at final values is restricted and weights for errors are chosen larger.

The minimal value of the given performance index is set f_N, as function of its initial error values e(0),

$$f_N[e(o)]=\underset{\substack{u(i)\\ i=0,1...,N-1}}{\mathrm{Min}} \sum_{k=1}^{N} [e'(k)Q(k)e(k)+u^2(k-1)] \qquad (9)$$

or the general form in the interval in [j-N].

$$f_N[e(j)]=\underset{\substack{u(i)\\ i=j...,N-1}}{\mathrm{Min}}[I_{N-j}] \qquad (10)$$

It is obvious that;

$$f_o[e(o)]=0 \qquad (11)$$

according to the principle of optimality, the following relations should hold,

$$f_{N-j}[e(j)]=\underset{u(j)}{\mathrm{Min}}\ [e'(j+1)Q(j+1)e(j+1)+u^2(j) +f_{N-(j+1)}[e(j+1)]] \qquad (12)$$

and the function f_N is obvious that which is expressed in the quadratic form of its present state e(k),

$$f_{N-j}[e(k)]=e'(j)P(j)e(j) \qquad (13)$$

$$f_{N-(j+1)}[e(j+1)]=e'(j+1)P(N-(j+1))e(j+1) \qquad (14)$$

where P should be sellected as positive defenite, substituting eqn(13) and eqn.(14) into eqn.(12) we can get;

$$e'(j)P(N-j)e(j)=\underset{u(j)}{\mathrm{Min}}[e'(j+1)[Q(j+1)+P(N-(j+1))] e(j+1)+u^2(j)]$$

$$=\underset{u(j)}{\mathrm{Min}}[e'(j+1)S(N-(j+1))e(j)+u^2(j)]$$

$$(15)$$

in the above equation, next relations are applied,

$$S(N-(j+1))=Q(j+1)+P(N-(j+1)) \qquad (16)$$

$$f_{N-j}[e(j)]=\underset{u(j)}{\mathrm{Min}}[[\phi(T)e(j)+h(T)u(j)]'S(N-(j+1))* [\phi(T)e(j)+h(T)u(j)]+u^2(j)] \qquad (17)$$

In fact the optimal control is determined differenciating the eqn.(17) with respect to u(j).

From the symmetricity of S( ), the optimal control at the jth step is,

$$u^{opt}(j) = -\frac{h'(T)S(N-(j+1))\phi(T)}{h'(T)S(N-(j+1))h(T)+1}e(j) \qquad (18)$$

The derived optimal control signal is to be realized in the form of feedback control calculation with the error state at that sampling point j.

THe gains for both position and velocity errors at that sampling time is given;

$$G(N-j) = -\frac{h'(T)S(N-(j+1))\phi(T)}{h'(T)S(N-(j+1))h(T)+1} \qquad (19)$$

From eqn.(17), the iteration of matrix P( ) is;

$$P(N-j) =\phi'(T)S(N-(j+1))\phi(T) + \phi'(T)S(N-(j+1))h(T)G(N-j) \qquad (20)$$

It is important that the synthesized gain patterns are independent of the amount of the speed difference and position difference between the shear and the point to be cut on the object.

For the special features of this type of shearing control, the blade velocity only at the time of cutting instance is strongly constrainted to coincide with the motion of the object.

In assigning the weighting factors [Q(k)] on the controlled error state, the position difference in the stage before the cutting instance is left free.

An example of determined gain patterns is shown in Fig.3. The terminal weight for position error and velocity error are tuned larger than the initial and central stages.

The synthesized time-varying gain pattern appears in a very characteristic form relating only with the inverse time axis from the terminal time.

The closed-loop configulation of this shearing control presents strong robustness for the uncertainties or the changes in the system parameters.

THE RESULTS OF SIMULATION STUDY:

For the idealized speed regulator of first order lag, the stability and the optimality of control operation is proven theoretically, but the real existence of the motor control system is constructed of more complicated parts as the armature circuit, current control circuit and voltage control circuit including some nonlinearity and uncertaities in model parameters.

A typical of speed regulation system is shown in Fig.4. For the lowest order approximation of this higher order model, first order linear model is assumed for control logic design and gain pattern determination stage.

To evaluate the feasibility of this proposed control logic in the simulation program, the synthesized gain patterns for the simplified linear model is combined into the higher order nonlinear motor model. The results of simulation study are shown in Fig.5.

Numerical comparation of the proposed control strategy over the conventional design is summerized in Table 1. The residual errors in the length and velocity at the time of cutting is greately improved.

In the simulation result, it is obvious that in spite of the greater gains of both position control and speed control loops, the resultant value of speed reference siganal is stays in the allowable band of limit.

The closed loop control gains are to be chosen much greater than the case of constant gain feed back control, which is derived through conventional way of control system design.

IMPLEMENTATION ON A PROCESS CONTROL COMPUTER:

The shearing control proposed in this paper functionate highly accurate cutting motion, the difference in both cutting length and velocity is adjusted simultaneously.

Increased amount of gain numbers in the close time region of the cutting instance will result satisfactorily smaller remainning offset in cut length and shearer velocity.

In Fig.6, control system configulation is shown, where synthesized time-varying gain pattern $[G_L, G_V]$ are stored in the machine memory and are read out in the order under the management of left time calculation module.

The synthesized time-varying gain pattern appear in a characteristic form relating to the inverse time axis from the terminal time.

Calculation of the optimal gains under the prescribed weights on errors is some complicated one for real time process control computers, which is not neccessary to be computed in real time. The gain pattern computation is run on some appropriate off-line machine other than the real time processor beforehand.

It simplifies the system configuration of the real time control system so much. The only task to be processed in real time is to determine the left time to the cutting terminal in the timing calculation module.

The time-varying feedback control gains are picked out according to the determined remainning time to cutting.

ACTUAL OPERATION RESULTS:

The shearing control system developed in this paper has been in commercial operation in many paper manufacturing plants and in the steel rolling processes. Some typical performance results recorded at a corrugated paper manufacturing plant are shown bellow.

The controled shear blade speed and motor current record is shown in Fig.7, blade speed is adjusted in order to get aimed cutting length and at the near of the terminal time of cutting start blade speed is made coincide with the object speed V_b. Motor current is regulated exactly in reasonable amount under the allowable overcurrent limitation no excess current is spent at the time of cutting.

The stability of cutting motion is well recognized in the figure.

Fig.8 is the cutting length distribution around the prescribed point, highly precise cutting operation can be appreciated.

Averaged error is ngligiblly small and the standard deviation around the nominal is reduced to 0.15[mm].

In Fig.9 the actual result of high speed cutting operation is shown sufficiently accurate cut point controlis proved at any operation speed. In this case of printed mark cutting the mark size is 5[mm] in width.

The object piece is cut at the real center of the aimed cutting zone at any speed up to the highest operation speed.

Fig.10 is the operation record of cutting in the acceleration stage, the sheet is cut uniformly into the appointed size while the object speed is increasing.

The blade shear the exact point length at the same speed with the object travelling at that cutting instance.

CONCLUSIONS:

Applying the terminal time constrained optimal regulator, simplified control system configuration of rotary shearing system is realized.

Picking up the appropreate point of stored gain patterns which is calculated on some off-line computer beforehand, the real time control system configuration is made compact.

Multivariable feedback control with pre-assigned time-varying closed loop gains works sufficientlly accurate.

The accuracy in both cut point length and blade velocity control has greately improved.

Feedback structure of this shearing control works effective in spite of the uncertainties in object dynamics or parameters aging.

The principle of this optimal shearing control is thought to be applicable for any type of flying shearer mechanism.

Refferences:

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Table 1. Compared cutting accuracy

	O.C = 300 [%]		O.C = 200 [%]		O.C = 150 [%]	
	L	V	L	V	L	V
conventional	0.45	-0.64	-0.95	165.0	-51.1	375.8
proposed	-0.02	-0.07	0.03	-1.52	0.10	-4.67

O.C for over current

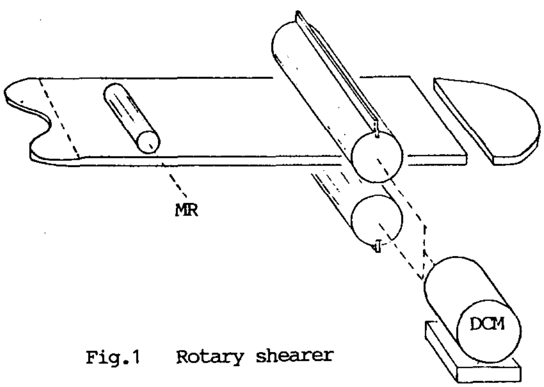

Fig.1 Rotary shearer

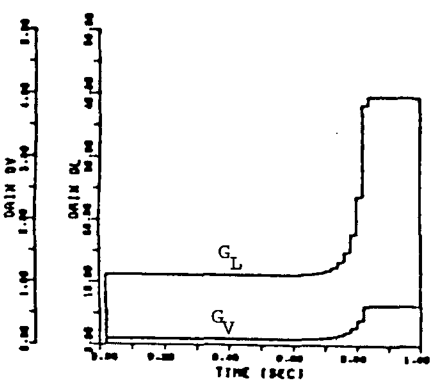

Fig.3 Synthesized gain pattern $[G_L, G_V]$

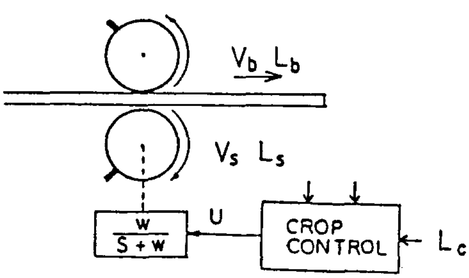

Fig.2 Optimal shearing control

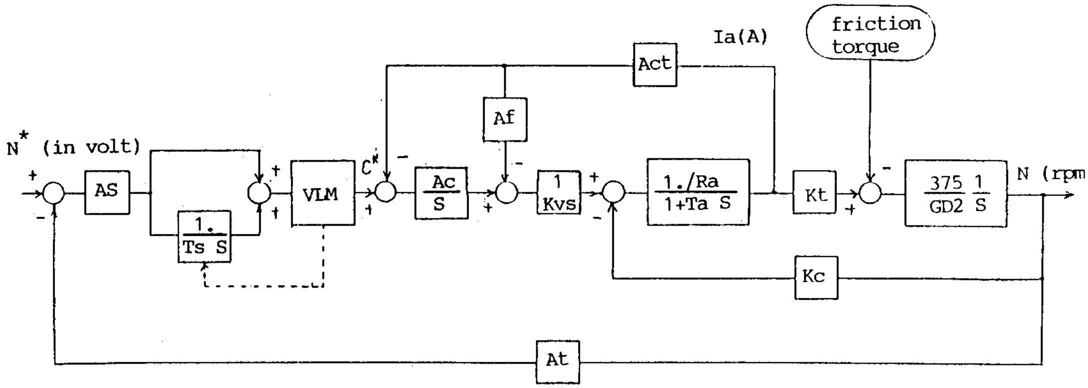

Fig.4 Speed regulator

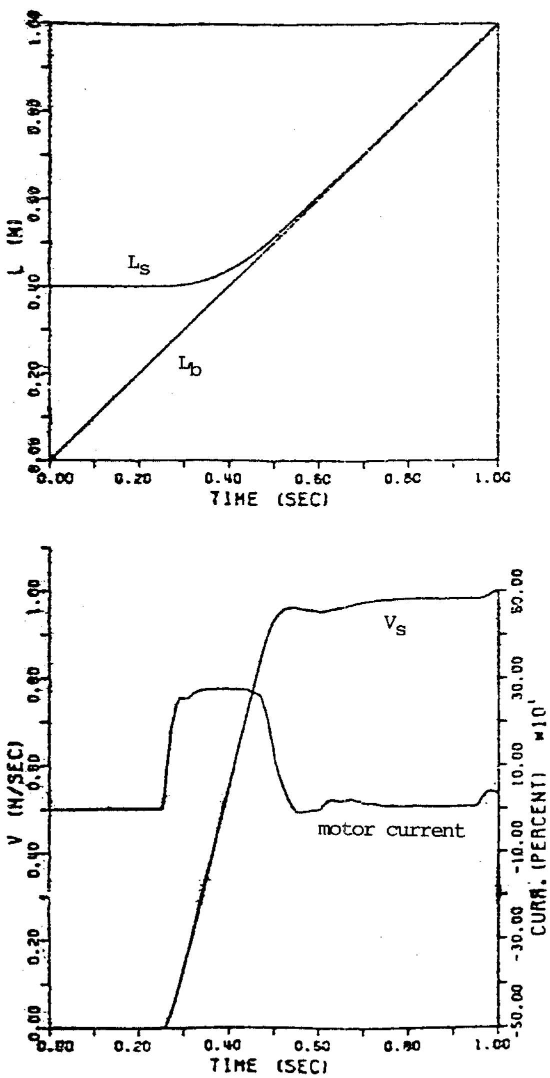

Fig.5 Simulated results

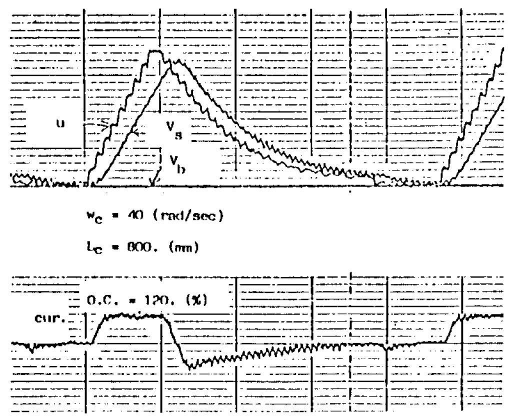

Fig.7 Operation result
[Velocity matching at the terminal]

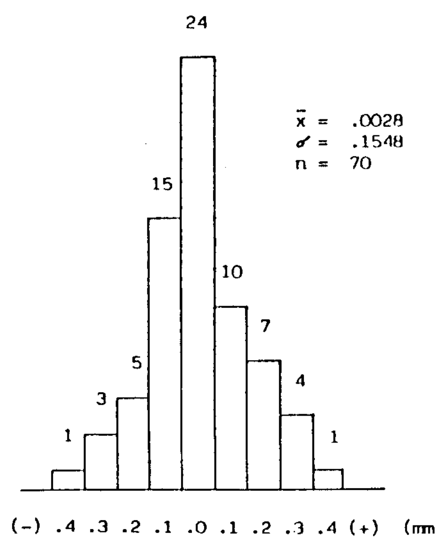

Fig.8 Cutting point histogram

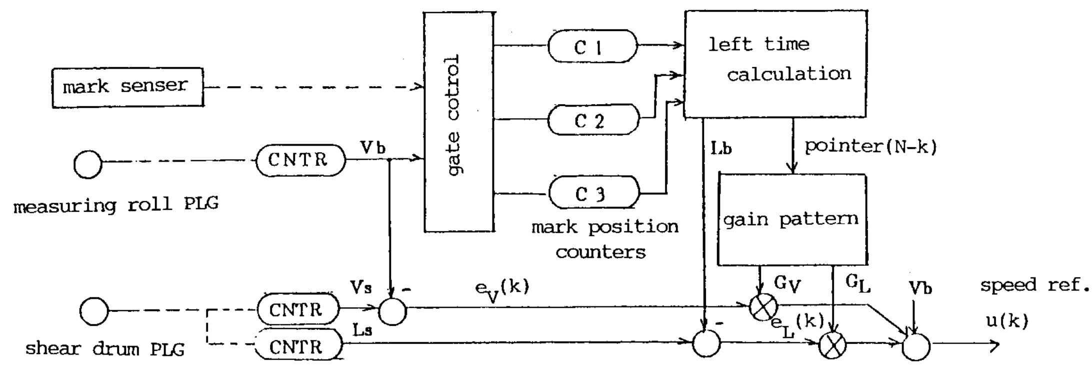

Fig.6 Control system configulation

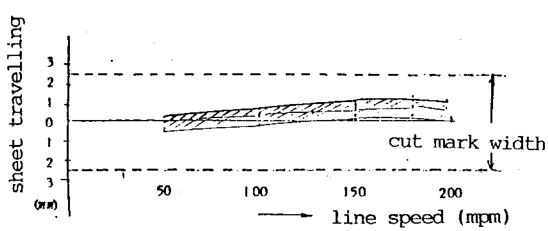

Fig.9 Actual result of high speed operation

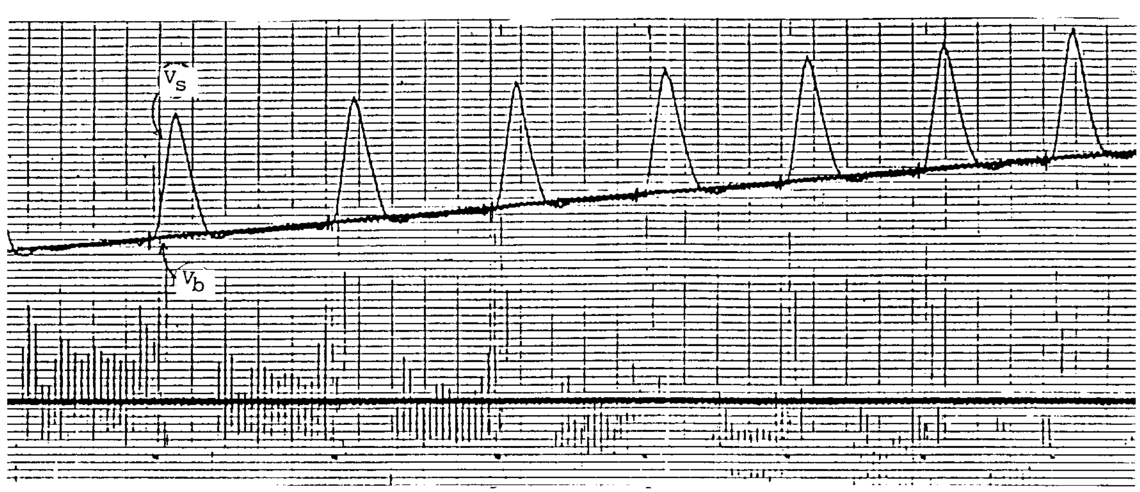

Fig.10 The result of acceleration operation