MODELLING AND SIMULATION OF TRANSIENT TENSION CONTROL SYSTEM FOR CONTINUOUS PROCESS LINE

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Abstract: Many types of transient tension control devices are used in continuous process lines(e.g.: CAL, CGL, ETL) to protect the process section from excess tension variation. Looping tower, tension bridle, tension control unit are said to be the most commonly used devices for those objects. But in this paper, we will discuss the tension control unit in viewpoint of modelling, dynamic behavior analysis, design for tension absorbtion, tension control mechanism, etc. *Copyright © 2000 IFAC*

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1. INTRODUCTION

Many types of tension control device are used in continuous process lines to protect the process section from the excess tension variation which arises in transient operation condition. Tension control unit(TCU) is the device that is used for that purpose in the steel strip processing lines which include continuous annealing line(CAL), continuous galvanizing line(CGL) and pickling line(PL). The process section of those lines(annealing section to CAL, galvanizing section to CGL) is so vulnerable to excess tension variation that various TCUs are applied to the boundary of that section. The tension control mechanism of the TCU is simple but its operation is so difficult that tuning of its controller needs meticulous care. The moving roll has the key role in a TCU. Its movability enables the TCU to accumulate or release a bit parts of steel strip rapidly for the purpose of tension regulation. The motion of a TCU is controlled by driving actuator(electric, pneumatic or hydraulic) or passively loaded by balanced weight and hinged lever arm.

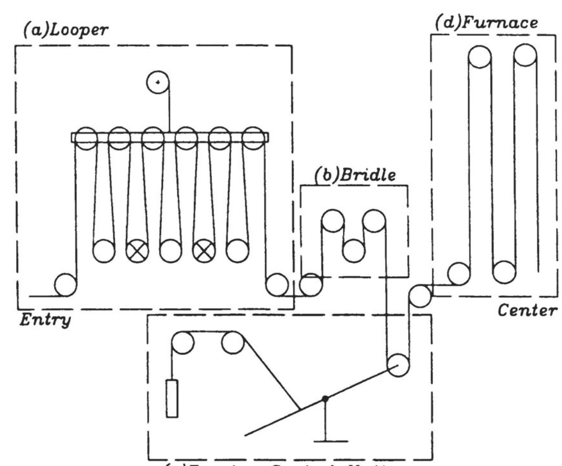

Fig. 1. Typical layout of Tension Control Devices in Steel Strip Processing Line:(a)Looper, (b)Tension Btidle, (c)Tension Control Unit

Modelling of this kind of control system was widely studied in such industries as paper, plastic film and printing machinery. But previously studied modeling was mainly for the light material handling industries and model nonlinearity such as moving roll mass effect was ignored. For the TCU is adopted to control the heavy steel strip, mass effects of its moving roll and lever arm cannot be ignored when this control system is modelled. Newly proposed TCU model in this paper includes 2 fixed roll and 1 moving roll. One fixed roll is positioned on the entry point of the TCU and the other is on the delivery point of it. Moving roll is attached to the balanced lever arm which is hinged at one point. Under the steady operation condition, lever arm is horizontally parallel to flour because counter weight is adjusted to balance the total weight of moving roll, strip tension and lever weight. But under the velocity transient(acceleration, deceleration) operation condition, lever arm will fluctuate because of the tension disturbance that inflows from the entry point of the TCU. This fluctuation is measured by the angle sensor attached to the lever arm hinge point and fed back to the motor driving system of the first fixed roll in the upper stream so as to regulate the lever arm angle to zero degree by motor speed control.

The TCU control system model could be divided to three parts of model element. One is the geometrical relationships between strips and lever arm. These relationships are given by the series of the equations representing the crossing angles and distances between the rolls. These equations are quite nonlinearly coupled between parameters. Another part of model is TCU dynamic equations. These equations are dynamic equations of 3 rolls and 1 lever arm. Each equation is represented as angular momentum equation of mass body. Another part of model is strip velocity-strain relationship. This model part also could be called strip tension mechanism. The principle of this model is mass flow conservation in the predefined control volume which is frequently seen in the field of continium mechanics. Particularly in this paper, we introduced the variable control volume to model the variable strip size.

The performance of the TCU could be evaluated on two design view points. One is the passive disturbance dissipation(damping) performance which is obtained by the structural design. A good design of the TCU structure will result in the good dynamic characteristics of the open loop control system transfer function. So as to get the good dynamic characteristics, we built dynamic control system model and analyzed its stability based on the classical control theory. Also we built the TCU structural(dimensional, mechanical) design guide to avoid the open loop control system unstability. The other view point is lever arm angle regulation performance by the feedback control of upper stream motor drive. The closed loop control from motor speed to lever arm was

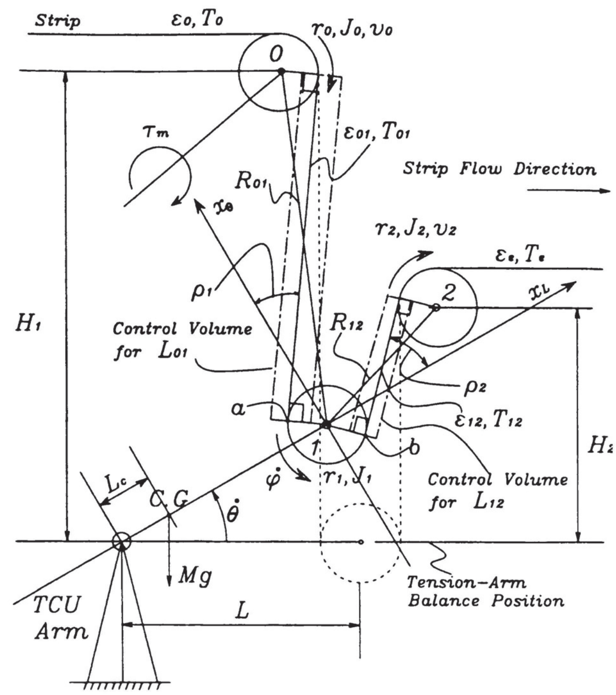

Fig. 2. TCU model of a CAL: dancer roll motion is constraned by rotating lever arm motion.

analyzed based on the classical control theory. A design method to increase the regulation performance and avoid unstability was studied. Optimal dimensional and mechanical design approach to satisfy the performance was discussed.

All design approaches were analyzed with the simulation of model and controller. Time domain and frequency domain simulations were done. All simulations were done by using a commercial CACSD package.

2. MODELLING OF THE TENSION CONTROL DEVICE

There are many previous studies of the modelling method to make mathematical equation describes the one part of manufacturing process of web, which is defined as such plate shape flexible material with very thin thickness and very narrow width compared with its logitudinal dimension as steel strip, paper, textile and polyethylene film (Reid *et al.* 1992), (Kesseler *et al.* 1984), (Carter 1965). In almost every case, mathematical equation was established based on the elastic behavior of web. Especially as for the TCU process model with dancer roll, see (Brandenburg and Karbacher 1981), (McDow and Rahn 1998). In Brandenburg's work, model was linearized and normalized to some variables, and dancer roll inertia was considered for design view point. In McDow's work, the model describes the light material handling process with nonlinear equations

Table 1. A sample operation condition of TCU process

v_N	mpm	350	Line Speed
r	mm	450	Roll Radius
T_N	kgf	857	Tension Regulation Target
t	mm	0.6	Strip Thickness
w	mm	1200	Strip Width
L	m	2.65	TCU Arm Length
L_c	m	1.245	Distance btw C.G of Arm
M	kg	3786	Mass of Arm
$\dot{\theta}_N$	rad/s	$\pi/15$	Steady State Arm Angle
J_r	kgm^2	300	Roll Inertia
J_t	kgm^2	16000	Arm Inertia

ignoring the dimensional and inertia effects of dancer roll.

In continuous annealing line(CAL) in which steel strip undergoes heat treatment, especially in the line for thick steel strip, the tension applied to the strip in process section is up to 1000kgf and the size of it is so big that the width is up to 1600mm. Therefore dancer roll and other strip transferring roll are so big that the effect of mass and dimension cannot be ignored. It is thought to be reasonable that mass effect and dimensional effect should be reflected in the TCU process model for such heavy steel strip handling process line as CAL. The schematic diagram of TCU process is described in Fig.2 and a sample operation condition is appeared in Table 1.

If the rotation angle of TCU arm(θ) is small, it would be possible to directly approximate the equations of motion and tension as in case of previously known ones. But the range of this angle is up to $\pm 45°$, it would be necessary to consider the applied direction of strip tension and the direction of motion of mass bodies. Process models related to the TCU can be devided to 3 relationships like these: (1)relationship between applied tension direction and direction of motion of roll, (2)dynamic motion equation of mass bodies consist of the TCU, (3)tension generation model induced from the roll circumferential speed and strip strain.

2.1 *Relationship of Tension Application Direction*

When each angle ρ_1, ρ_2 is defined as the cross angle between the orthogonal axis x_θ, x_L, which is located on the TCU arm, and strip span R_{01}, R_{12}, which is tightly wraped and streched from roll 0 to roll 2, it can be described like this below.

$$\rho_1 = \theta + \theta_1 + \alpha - \pi/2 \tag{1}$$

$$\rho_2 = -\theta + \theta_2 + \beta \tag{2}$$

where each variable θ_1,θ_2,α,β is given by

$$\tan\alpha = \frac{H_1 - L\sin\theta}{r_0 + r_1 - L(1-\cos\theta)} \tag{3}$$

$$\tan\beta = \frac{H_2 - L\sin\theta}{r_1 + r_2 - L(1-\cos\theta)} \tag{4}$$

$$\sin\theta_1 = \frac{r_0 + r_1}{R_{01}} \tag{5}$$

$$\sin\theta_2 = \frac{r_1 + r_2}{R_{12}} \tag{6}$$

and each strip length R_{01},R_{12} is given by

$$R_{01} = \sqrt{(H_1 - L\sin\theta)^2 + \{r_0 + r_1 - L(1-\cos\theta)\}^2}$$

$$R_{12} = \sqrt{(H_2 - L\sin\theta)^2 + \{r_1 + r_2 - L(1-\cos\theta)\}^2}$$

2.2 *Dynamic Motion Equation of TCU*

Motion equations of TCU arm and 3 rolls are obtained from the rotational momentum principle of mass body.

$$J_0\frac{dv_0}{dt} = (T_{01} - T_0)r_0^2 + \tau_m \tag{7}$$

$$J_1\ddot{\varphi} = (T_{12} - T_{01})r_1 \tag{8}$$

$$J_2\frac{dv_2}{dt} = (T_e - T_{12})r_2^2 \tag{9}$$

$$J_t\ddot{\theta} = T_{12}(L\sin\rho_2 + r_1) + T_{01}(L\cos\rho_1 - r_1) - MgL_c\cos\theta \tag{10}$$

where loss term due to the mechanical friction is ignored assuming that it is relatively small compared with intia term.

2.3 *Strip Speed-Strain Relationship*

In TCU strip handling process, a moving roll is located amid two consecutive fixed rolls and accumulated strip length is variable depending on the position of that moving roll. For such process can be found in the steel accumulating process in which similiar speed-strain relationship was defined(Jee *et al.* 1998), the same approach can be applied to this TCU process. In this case, two control volumes corresponding to strip R_{01}, R_{12} are set to define mass flows through the control volume. The control volume boundary is consist of strip-roll contact point and parallel line along the strip(see Fig. 2), and its volume is variable depending on the moving roll position. From the summing of infow and outflow of strip mass flow through a control volume, speed-strain relationship for the two strip span in uniaxial logitudinal mode is given by

$$\frac{d}{dt}\left(\frac{R_{01}(t)}{1+\varepsilon_{01}(t)}\right) = \frac{v_0(t)}{1+\varepsilon_0(t)} - \frac{v_{1a}(t)}{1+\varepsilon_{01}(t)} \tag{11}$$

$$\frac{d}{dt}\left(\frac{R_{12}(t)}{1+\varepsilon_{12}(t)}\right) = \frac{v_{1b}(t)}{1+\varepsilon_{01}(t)} - \frac{v_2(t)}{1+\varepsilon_{12}(t)} \quad (12)$$

where v_{1a}, v_{1b} is relative velocity of steel contact point a, b respect to each control volume and given by $v_{1a} = v_{1b} = r_1\dot{\varphi}$. Practically in continuous stip processing line, strain that experienced by a strip span is very small. For example, if thickness of strip is 0.2mm and width of it is 1200mm, and applied tension is 1000kgf, then this strip span experiences the strain amount to 0.0002. Therefore the terms with inverse of strain in above equations can be approximated through series expansion. The new relationship is obtained by rearrangement of that result like this below.

$$R_{01}\frac{d\varepsilon_{01}}{dt} = r_1\dot{\varphi}(1-\varepsilon_{01}) - v_0(1-\varepsilon_0) - (1-\varepsilon_{01})L\dot{\theta}\cos\rho_1 \quad (13)$$

$$R_{12}\frac{d\varepsilon_{12}}{dt} = v_2(1-\varepsilon_{12}) - r_2\dot{\varphi}(1-\varepsilon_{01}) + (1-\varepsilon_{12})L\dot{\theta}\sin\rho_2 \quad (14)$$

In above two equations, the last term means strip length variation due to the rotational motion of TCU arm.

3. TENSION CONTROL PROCESS IN TCU

Althogh the TCU that adopted in countinuous process line is applied to control strip tension, it does not use directly measured tension value as the feedback signal but senses tension transient indirectly when it activates control action. In short, as shown in Fig. 2., the counterweight that is located in the oposite side of the dancer roll is adjusted so that angular momentum balance should be achieved within the TCU lever arm mass body system and the TCU lever arm is maintained parallel to horizontal floor in steady state process. Actually in modern steel strip processing line, counterweight application point is adjusted by electrically driven linear guide positioning system. Under transient process state, sinusoidal tension disturbance appears and lever arm angle θ varies correspondingly. So, TCU controller should make the control output for roll drive control system of upper stream roll 0 so that arm lever angle θ be maintained 0 under any circumstance. For example, if the lever angle θ becomes any posive angle abruptly, then rotation speed of roll 0 should be increased so as to diminish the strip tension and make the arm lever angle come back to 0. The principle of TCU is described as a block diagram in Fig. 3. It is based on the linearized model of original TCU process model that was established in the previous chapter. It can be seen in Fig. 3 that one loop PI controller is used as the roll 0 drive controller to regulate the arm lever angle.

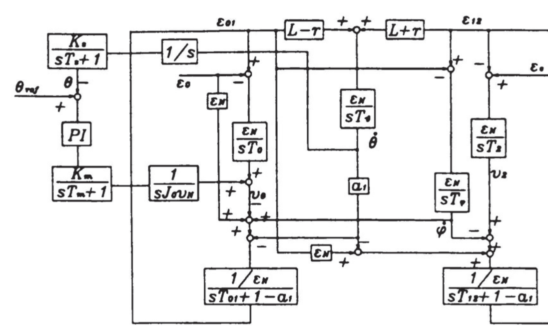

Fig. 3. TCU control system block diagram which describes the transferring characteristics of tension control system

4. MECHANISM DESIGN BY TRANSFER FUNCTION CHARACTERISTICS ANALYSIS

Typical tension disturbance arises in continuous process line is mostly sinusoidal waveform shape. The frequency bandwidth of the tension disturbance depends on the upper stream tension control devices such as looper, tension bridle. For example, if the Looper carriage driving mechanism is chain/sprocket, the bandwidth of tension disturbance is formed in higher frequency than that in the case of Looer driving mechanism with wire rope. Such tension disturbance waveform is partly damped and distorted when strip passes through the TCU. The open loop trnasfer function analysis in frequency domain has been done usualy for this passive damping characteristics of a system.

To analyse the passive disturbance characteristics of a TCU in frequency domain, the open loop transfer function of strain of the strip span that exits from roll 2 to strain of the strip span that enter into roll 0 is formulated based on the TCU control system block diagram(Fig. 3). Magnitude plot of Bode plot of the open loop system that described by this transfer function is shown Fig. 4. As shown in this figure, output of the system is damped with constant rate in bandwidth up to 100rad/s, two resonant peaks appear and the band that damping rate varies with constant rate appears in higher frequencies.

The effects on this transfer function characteristics depending on the mechanical factors of a TCU were investigated in various operating conditions. The results shows that the damping effect of a TCU dominantly depends on inertia moment of dancer roll(J_1) term and the damping effect increases as the inertia value rises. But too much increased inertia term will introduce system unstability because some characteristic equation roots of the transfer function approaches the imaginery axis and it will deteriorate the oscillation characteristics of the system as it increases. For that reason, optimum geometrical design approach should be practiced so that both of the disturbance damping effect and arm oscillation characteristics are satisfied when TCU arm is designed.

Up to the previous paragraph, passive tension damping effect of TCU was investigated by open loop transfer function analysis. On the other hand, active tesion control performance also can be investigated if the closed loop trnasfer function which includes PI controller(Fig. 3) is analysed. As in the case of open loop analysis, if the tension disturbance that makes ε_0 fluctuate is introduced to the system shown Fig. 3, tension controller would make the controller output to reject the disturbance. In Fig. 5, frequency domain charactenistics of closed loop transfer function obtained based on the numerical data of Table 1 is shown. In such classical control system analyses, it is typical to analyse frequency domain characteristics of the system by obtaining Bode plot or Root Locus. Thus, in this study, frequency domain characteristics of the system was investigated with various P gain of PI controller. As shown in Fig. 5, there is no difference from the case of open loop transfer function except for the low frequency pass band shaped in lower frequency when the P gain is low. But when the P gain increases, it can be seen that damping rate becomes lower in some low frequency band(if K_p=50, band lower than 10rad/s). Although the better tension disturbance rejection performance can be obtained with higher P gain, charateristic equation roots of closed loop transfer function can appears in the right half plane of s-plane and it means the unstability of the system(Table 2). For this reason, if active TCU control performance were pursued added to the passive tension disturbance damping performance, it would be necessary to carry out controller gain optimization process like this analysis.

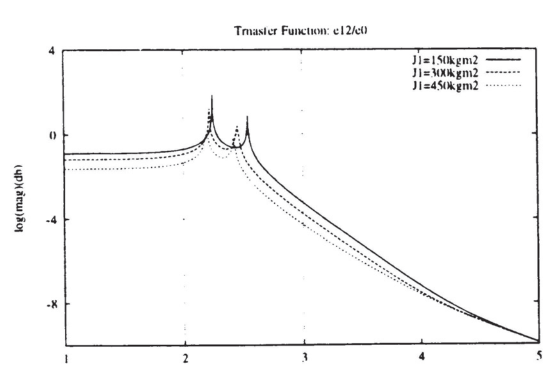

Fig. 4. Open loop transfer function of exit point strip strain to entry point strip strain ($\varepsilon_{12}/\varepsilon_0$)

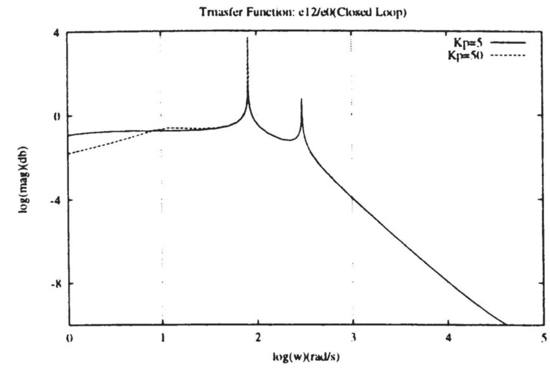

Fig. 5. Closed loop transfer function of exit point strip strain to entry point strip strain ($\varepsilon_{12}/\varepsilon_0$)

Table 2. Characteristic equation roots of closed loop transfer function

K_p=5	K_p=50
0	0
-0.310+299.8i	-0.327+299.6i
-0.310-299.8i	-0.327-299.6i
-0.037+81.9i	0.001+81.7i
-0.037-81.9i	0.001-81.7i
-9.928	-5.602+9.370i
-1.191	-5.602-9.370i
-2.0e-6	-2.0e-7

5. CONCLUSION

The process modelling of the TCU that is used as the transient tension control device of continuous process line, the principle of indirect tension control method by TCU lever arm, design consideration of transient tension control device based on the linearized model and frequency domain simulation was discussed in this paper.

Practically, it is more stressed on the passive tension disturbance damping aspect than active control one in continuous process line of modern steel works when TCU is adopted as a tension control device. So, it remains much rooms to apply the control system design concept and simulation approach discussed in this paper. Moreover, nonlinear modelling approach for the TCU of heavy strip line can be applied to the controller design with nonlinearity.

6. REFERENCES

Brandenburg, G. and N. Karbacher (1981). Ein beitrag zur optimierung von regelkreisen mit taenzerwalzen bei kontinuierlichen fertigunsanlagen. *Relgelungstechink* **29**, 428–433.

Carter, W.C. (1965). Reducing transient strains in elastic-strip processes. *Control Engineering* **3**, 84-87.

Jee, C.W., M.K. Park and C.J. Jin (1998). A study on speed-tension control methodology