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# Development of High-Response Looper Control System Based on Multivariable Control Theory

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**Abstract:**

*A new two-degrees-of-freedom control system was developed with the addition of a disturbance compensation function in order to improve the insufficient disturbance control capability of conventional multivariable noninteracting control systems. Since the disturbance compensator is designed by the H-infinity theory, the control performance of the new system can be improved while considering its robustness. Also, as the whole system is noninteracting, it permits relatively easy fine-tuning on site. When this system was applied to the strip tension and looper angle control at a hot strip finishing mill train, computer simulation confirmed that it produces little strip tension or looper angle variation.*

## 1. Introduction

In hot strip finish rolling, variation in the interstand strip tension has a great impact on dimensional accuracy and threading performance, and that in looper angle hampers the stability of mill operations. It is desirable that the interstand strip tension and looper angle be kept constant, but their mutual interaction makes it difficult to control them satisfactorily.

At present, Nippon Steel adopts noninteracting control[1] and optimal control[2,3] as main control schemes for its hot strip mills. In noninteracting control, the interstand strip tension control system and the looper angle control system are separated by a cross controller and independently controlled as single-input single-output (SISO) systems. In optimal control, the strip tension and looper angle control systems are handled as multivariable systems. Noninteracting control fails to completely suppress the interstand tension and looper angle variations, while optimal control involves difficulties in fine-tuning on site.

The design of multivariable control systems by the H-infinity theory has lately attracted considerable attention[4,5]. This theory allows control systems to be designed to suit specific frequency ranges. For example, robust stability can be increased in a certain frequency range, and the effect of system sensitivity or disturbance can be decreased in another frequency range.

A new control system that can fully suppress the strip tension and looper angle variations was developed by combining the conventional noninteracting control with a compensator designed by the H-infinity theory. The design technique and simulation results are described below.

## 2. Controlled System

**Fig. 1** shows the constitution of a hot strip mill line. The slab to be rolled into strip is first reheated to the specified temperature in the reheating furnace, and is then rolled through roughing and finishing mill train to the specified size. Upon leaving the last finishing mill train, the strip is immediately cooled on the runout table (ROT) and is finally coiled by the downcoiler.

The finishing mill train in **Fig. 1** is enlarged in **Fig. 2**. In continuous rolling, the tension applied to the strip between stands has a great impact on the dimensional accuracy and threading performance of the strip. A device, called the looper, is therefore installed between stands. Since the looper is limited in the operating range, however, the looper angle should be maintained at a constant value to provide against contingencies. The interstand strip tension and the looper angle are simultaneously con-

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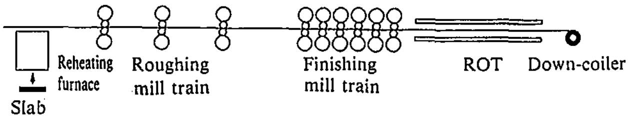



**Fig. 1** Constitution of hot strip rolling line

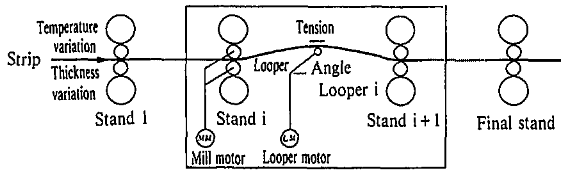



**Fig. 2** Constitution of finishing mill train

trolled by using a looper motor (LM) to drive each looper and a mill motor (MM) to drive each stand. Namely, the controlled system is a multivariable system with two inputs and two outputs.

Usually, variations in strip tension and looper angle during rolling are caused mainly by non-uniform slab heating in the reheating furnace called skid marks (see **Fig. 3**). When a slab nonuniformly reheated as shown in **Fig. 3** is rolled on the roughing train, strip temperature and thickness variations affect rolling on the finishing mill train. These disturbances enter the finishing mill control system directly or indirectly through other stands, and vary the strip tension and looper angle. The frequency of the skid mark disturbance changes in proportion to the rolling speed and is considered to range from 0 to 2 rad/s according to the operating conditions of the mill.

## 3. Conventional Control Systems

Steelworks have developed various systems of strip tension and looper control. Presented below are outlines of and problems with noninteracting control and optimal control as typical control systems.

### 3.1 Noninteracting control[1)]

A block diagram of the conventional noninteracting control system is shown in **Fig. 4**. The looper control system and strip tension control system that interact are made apparently noninteracting by a cross controller of the pre-compensator type and are independently controlled by separate proportional-integral (PI) controllers. This control system has the following advantages and disadvantages:

Advantages

(1) Since the system can be designed as a single-input single-output (SISO) control system, its control performance can be easily designed and adjusted.

(2) Since the system is noninteracting, the strip tension does not vary even if the reference input of the looper angle is changed.

Disadvantages

(1) The PI control gain cannot be increased to the extent of satisfying the strip tension and looper variation specifications.

(2) Since strip tension variations are controlled by controlling the mill motor speed, the loopers are not best utilized.

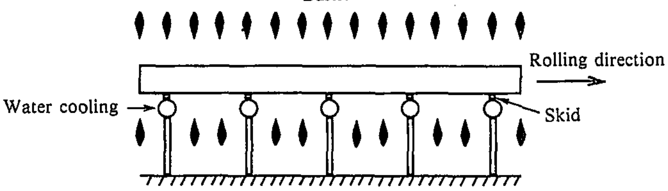
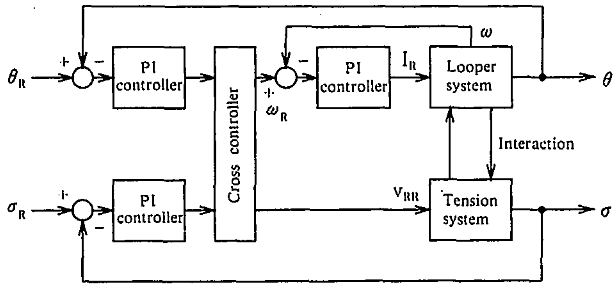
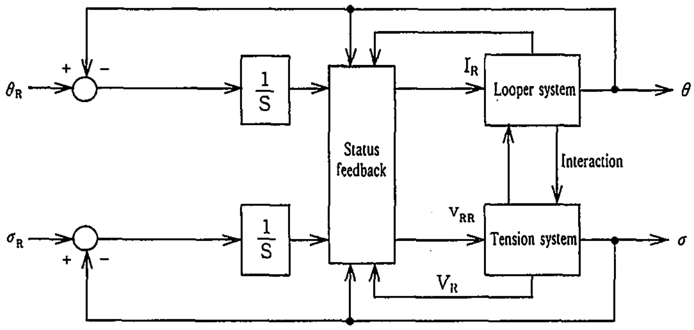



**Fig. 3** Slab in reheating furnace




$\theta$ = looper angle; $\sigma$ = strip tension; $\omega$ = looper motor speed; $\theta_R$ = reference input of looper angle; $\sigma_R$ = reference input of tension; $\omega_R$ = corrected value of looper motor speed; $V_{RR}$ = corrected value of roll peripheral speed; $I_R$ = looper motor current

**Fig. 4** Conventional noninteracting control system




$V_R$ = roll peripheral speed

**Fig. 5** Optimal control

### 3.2 Optimal control[2,3)]

A block diagram of the conventional optimal control system is given in **Fig. 5**. In the figure, $\theta$, $\sigma$, $\omega$, $V_R$, the integrated value of angle deviation and the integrated value of tension deviation are used as state vectors x, and $\omega_R$ and $V_{RR}$ are used as input vectors u. The controller K is obtained to minimize the quadratic performance index J in Eq. (1), and the state feedback $u = -Kx$ is carried out. The weighting matrices Q ($\geqq 0$) and R ($> 0$) are square matrices of constants to determine the control performance.

$$J=\int_0^{\infty}(x^TQx+u^TRu)\,dt \qquad \cdots\cdots(1)$$

The optimal control system has the following advantage and disadvantages:

Advantage

(1) Since the controlled system is treated as a multivariable system, the looper motors and mill motors can be controlled in unison to enhance the control performance.

Disadvantages

(1) Since weighting matrix selection and control performance do not correlate on a one-to-one basis, it is difficult to design the control performance and adjust the controller parameters

on site.

(2) Since the control system is not of the noninteracting type, the strip tension varies when the reference input of the looper angle is changed.

## 4. New Control System

### 4.1 Description

A new control system based on the H-infinity theory was developed to solve the shortcomings of the conventional noninteracting control system and optimal control system mentioned above. A block diagram of the new control system is shown in **Fig. 6**. The composition of the new control system is such that process models of the looper system and the tension system and a controller (disturbance compensator) designed on the basis of the H-infinity theory[4,5] are added to a conventional noninteracting control system. The disturbance compensator is insensitive to variations in the reference input of the looper angle and the strip tension, and operates only when the looper angle and the strip tension vary under the influence of the disturbances. Since the response to variations in the reference input can be designed as done in the conventional noninteracting control system, the advantages of the noninteracting control system described in the previous chapter can be directly utilized.

To suppress the effects of disturbance by the disturbance controller, the gain of the PI controllers need not be raised to excess. Since the disturbance controller is designed as a two-input two-output system, the variations in the looper angle and strip tension can be efficiently controlled by simultaneously operating both the looper and mill motors.

### 4.2 Design technique

This design scheme can be used in controlling not only the strip tension and looper angle, but also general multiple-input multiple-output (MIMO) control systems. The design technique is explained here taking as an example the general MIMO system illustrated in **Fig. 7**.

Assuming that the signal line ① in **Fig. 7** is open, the cross controller H(S) and the main controller C(S) are designed according to the conventional noninteracting control. That is, H(S) is designed to make $G_1(S)H(S)$ a diagonal matrix, and the transfer function from the virtual input v to the control output y is made noninteracting. Each control loop is regarded as a single-input single-output system, and C(S) is sequentially designed as a PI or PID controller, for example. The control output y is given by

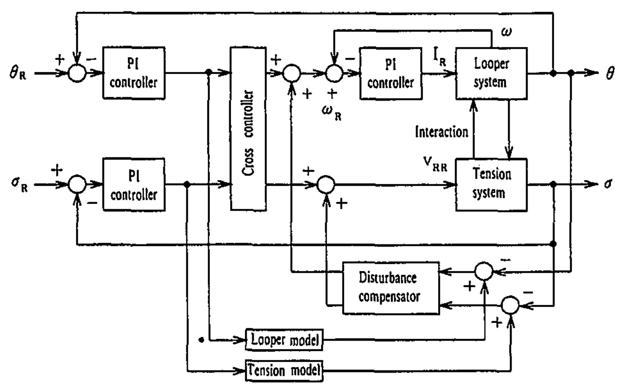
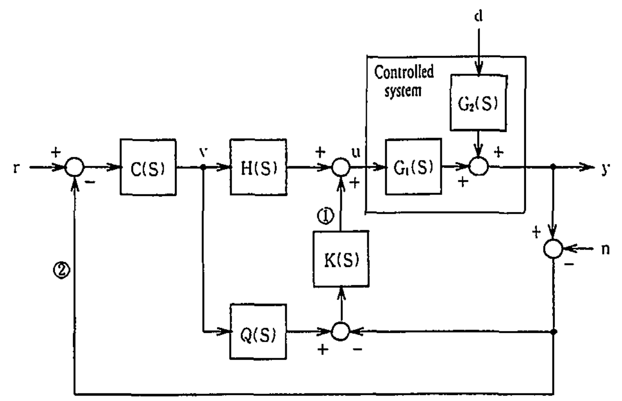



**Fig. 6** New control system




y = control output (m × 1); u = operating input (m × 1);
r = reference input (m × 1); v = virtual input (m × 1);
d = disturbance (p × 1); n = noise (m × 1);
$G_1(S)$ = transfer function of controlled system (m × m);
$G_2(S)$ = transfer function of controlled system (m × p);
C(S) = main controller (m × m); H(S) = cross controller (m × m);
Q(S) = plant model (m × m); K(S) = disturbance compensator (m × m);
m = number of inputs and outputs; p = number of disturbances

**Fig. 7** General scheme of new control system

$$y = R(S)r + S_C(S)d + T_C(S)n \quad \cdots\cdots(2)$$
$$R(S) = (I + G_1(S)H(S)C(S))^{-1} \cdot G_1(S)H(S)C(S)$$
$$S_C(S) = (I + G_1(S)H(S)C(S))^{-1}G_2(S)$$
$$T_C(S) = I - (I + G_1(S)H(S)C(S))^{-1}$$

where I is a unit matrix.

Then, the plant model Q(S) is made equal to the transfer function $G_1(S)H(S)$ from the virtual input v to the control output y.

$$Q(S) = G_1(S)H(S) \quad \cdots\cdots(3)$$

When the signal line ② is cut off in the block diagram of **Fig. 7**, the control output y is given by

$$y = Q(S)v + S_K(S)d + T_K(S)n \quad \cdots\cdots(4)$$
$$S_K(S) = (I + G_1(S)K(S))^{-1}G_2(S)$$
$$T_K(S) = I - (I + G_1(S)K(S))^{-1}$$

Since Q(S) is a transfer function that does not depend on K(S), the response to the reference input does not depend on K(S) if C(S) is designed by regarding the virtual input v as a new control input.

When the signal lines ① and ② are both connected in the block diagram of **Fig. 7**, control output y is given

$$y = R(S)r + S(S)d + T(S)n \quad \cdots\cdots(5)$$
$$S(S) = (I + Q(S)C(S))^{-1}S_K(S)$$
$$T(S) = T_C(S) + (I + Q(S)C(S))^{-1}T_K(S)$$

The response of control output y to reference input r becomes the same as expressed by Eq. (2) and does not depend on K(S). In contrast, the response of control output y to disturbance d is determined by K(S). If K(S) is properly designed, therefore, the effect of disturbance d can be reduced without changing the response to reference input r.

Lastly, disturbance compensator K(S) is designed. Equation (5) shows that the effect of disturbance d on control output y can be judged according to the magnitude of S(S). H-infinity norm is adopted as an index for measuring the magnitude of S(S). The H-infinity norm is taken as an extension of the gain of a single-input single-output transfer function into a multiple-input multiple-output transfer function. If F(S) is a stable and proper real rational transfer function matrix, the H-infinity norm is defined by

$$\|F(S)\|_\infty = \sup\sqrt{\lambda_{max}(F(j\omega)^*F(j\omega))} \quad \cdots\cdots(6)$$

where $\lambda_{max}(\cdot)$ is the maximum eigenvalue, and the symbol * denotes a complex conjugate transpose.

The following hold for $\|S(S)\|_\infty$ and $\|T(S)\|_\infty$ according to the property of the norm:

$$\|S(S)\|_\infty \leqq \|(I+Q(S)C(S))^{-1}\|_\infty \|S_K(S)\|_\infty \quad \cdots\cdots(7)$$

$$\|T(S)\|_\infty \leqq \|T_C(S)\|_\infty + \|(I+Q(S)C(S))^{-1}\|_\infty \|T_K(S)\|_\infty \quad \cdots\cdots(8)$$

If K(S) is designed to reduce both $\|S_K(S)\|_\infty$ and $\|T_K(S)\|_\infty$, therefore, the effect of disturbance d can be reduced without amplifying the effect of noise n as compared with the conventional noninteracting control system. When an unstructured multiplicative perturbation is assumed, the effect of disturbance d can be reduced without appreciably deteriorating the robust stability. Since it is practically impossible to reduce both $\|S_K(S)\|_\infty$ and $\|T_K(S)\|_\infty$ over the entire frequency range of concern, the system must be designed by dividing the frequency ranges of $\|S_K(S)\|_\infty$ and $\|T_K(S)\|_\infty$ so that $\|S_K(S)\|_\infty$ can be reduced only in the frequency range where disturbance d is present and $\|T_K(S)\|_\infty$ can be reduced only in the frequency range where importance is attached to both the noise and robust stability[4,5].

### 4.3 Relationship between disturbance control capability and robust stability

Study was made of how the disturbance control capability and robust stability would change with the gain of main controller C(S) and the gain of disturbance compensator K(S) when the new control system was applied to strip tension control and looper control.

The study results are as shown in **Fig. 8**. The disturbance control capability is the value of $\|S(S)\|_\infty^{-1}$ at the frequency of 1 rad/s, and the robust stability is the value of $\|T_K(S)\|_\infty^{-1}$ at the frequency of 20 rad/s. The C gain is the gain by which C(S) is multiplied, and the K gain is the gain by which K(S) is multiplied. From **Fig. 8**, the following can be said:

C gain ··· Small { Disturbance control capability ··· Decreases; Robust stability ··· Rises }

K gain ··· Small { Disturbance control capability ··· Decreases; Robust stability ··· Rises }

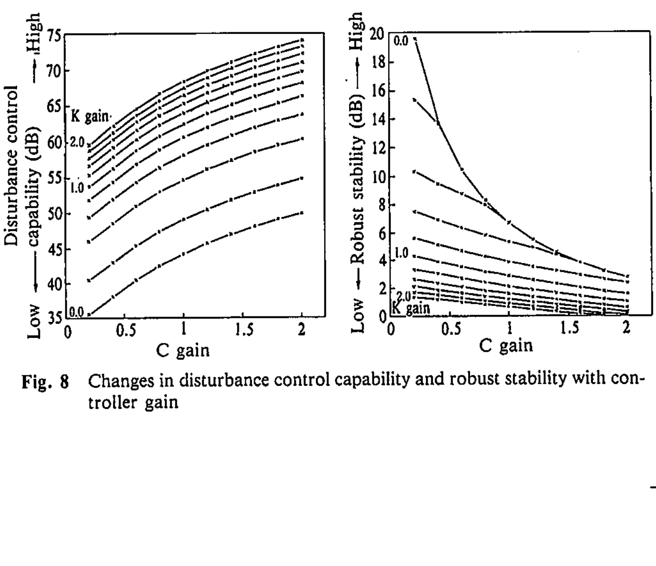



**Fig. 8** Changes in disturbance control capability and robust stability with controller gain

From Eq. (5),

C gain ··· 0 $\quad T(S) \rightarrow T_K(S)$

K gain ··· 0 $\quad T(S) \rightarrow T_C(S)$

The robust stability of the whole system approaches but does not exceed the robust stability of the corresponding controller. When the robust stability of the whole system need be reduced further, either or both of the C gain and the K gain must be reduced at the sacrifice of the disturbance control capability.

## 5. Simulation

The new control system is compared with the conventional noninteracting control system by simulation.

### 5.1 Frequency response

Assuming that disturbance is introduced from the interstand strip speed, the frequency responses of the effect of disturbance and the effect of sensor noise are shown in **Fig. 9**. The effect of disturbance is denoted by the maximum gain of transfer function from the strip speed disturbance to the looper angle and strip tension. The effect of sensor noise is denoted by the maximum gain of transfer function from the sensor signal to the looper angle and strip tension. The dotted lines indicate the results of the conventional noninteracting control system, and the solid lines are for the results of the new control system. From **Fig. 9**, it can be seen that the effect of disturbance is considerably lower than with the conventional control system in the frequency range of 0 to 2 rad/s where there are skid marks, while the effect of sensor noise makes practically no difference between the two systems.

### 5.2 Time response

The time response of the new control system was simulated in comparison with the conventional noninteracting control system. The rolling of strip with temperature variation of ±40°C and thickness variation of ±1.0 mm as skid mark disturbance was simulated using a six-stand hot rolling dynamic simulator. For 30 seconds after the start of the simulation, all the loopers were controlled by the conventional noninteracting control system, but thereafter the No. 3 to No. 5 loopers were switched to

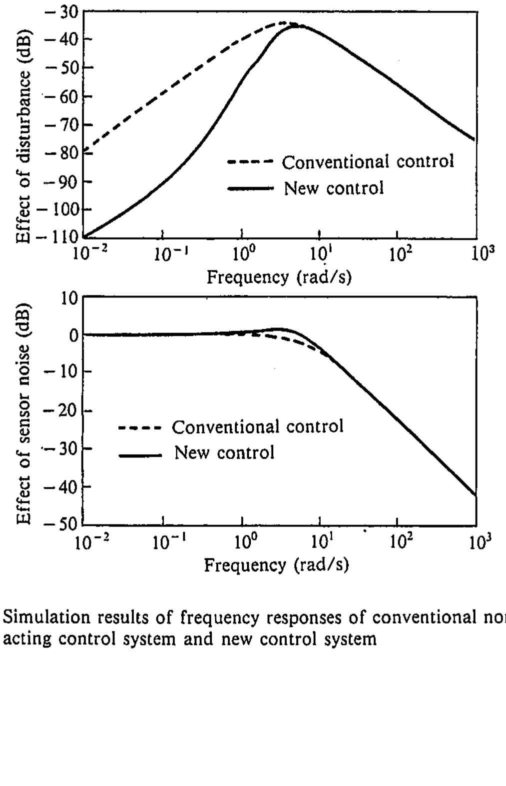



**Fig. 9** Simulation results of frequency responses of conventional noninteracting control system and new control system

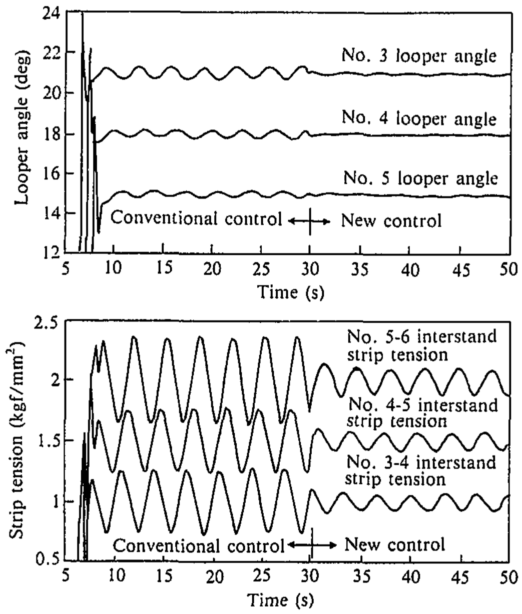



**Fig. 10** Simulation results of time responses of conventional interacting control system and new control system

control by the new control system. **Fig. 10** shows the time response data of the looper angle for No. 3 to No. 5 loopers and of the corresponding interstand strip tension. It can be seen there that the new control system performs better than the conventional noninteracting control system in terms of both the looper angle and strip tension.

## 6. Conclusions

The technique of improving the disturbance control capability of noninteracting control systems by adding a new controller designed on the basis of the H-infinity theory has been explained above. The effectiveness of the design technique was demonstrated by simulation.

The validity of the new control system will be verified on actual hot strip mills.

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