Multivariable Controls Of A Hot Strip Finishing Mill Interstand

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Abstract: In order to stabilize the rolling operation and to maintain product quality in a hot strip finishing mill, it is necessary to control the tension applied to the strip and the looper angle in interstand within their reference values.

In this paper, we develop different laws of interstand control to improve tension strip and looper angle accuracy. The criterion of performance comparison is the rejection of perturbation on these two variables.

The advanced interstand controls are :

1) the conventional looper control,
2) decoupling control for looper system in frequency domain or state space,
3) interstand multivariable control based on optimal control theory in state space.

This study presents a discussion and application of these new looper controls which are compared to the conventional one, orientating the regulation structure choice to be implanted in the future.

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1. Introduction

Loopers located between stands in a hot strip finishing mill perform at least two important functions : prevention of changes in the width and thickness of the strip by regulating interstand tension at a desired value and elimination of an excessive strip loop between stands, and provision of stable rolling operation by maintaining the looper angle at a desired value.

Figure 1 shows the configuration of the discussed processes and controllers. Looper controllers detect the looper angle θ to control the rolling motor speed of the upstream stand to achieve the aimed looper angle and also to control the looper motor torque to achieve the aimed strip tension considering the material weight and rigidity and the looper weight.

The controlled system is a multivariable system with two inputs and two outputs. The disturbances entering the looper control system are mainly of the interstand flow variation type $(v_1 - v_2)$.

In general, we will cite the skid marks due to non-uniform slab heating in the reheating furnace, and work and back-up rolls' eccentricity (out of roundness type defects) which generate periodic variations of the work roll gap in a stand, and so variations in thickness and material flow during rolling.

These disturbances severely influence the strip tension and looper angle performances.

The frequency of the skid mark disturbance is considered to range from 0.6 to 1.3 rad/s, while the eccentricity disturbance frequency covers the domain [1.7,28] rad/s for all stands of the finishing mill. For a given interstand, the eccentricity of upstream stands is preponderant.

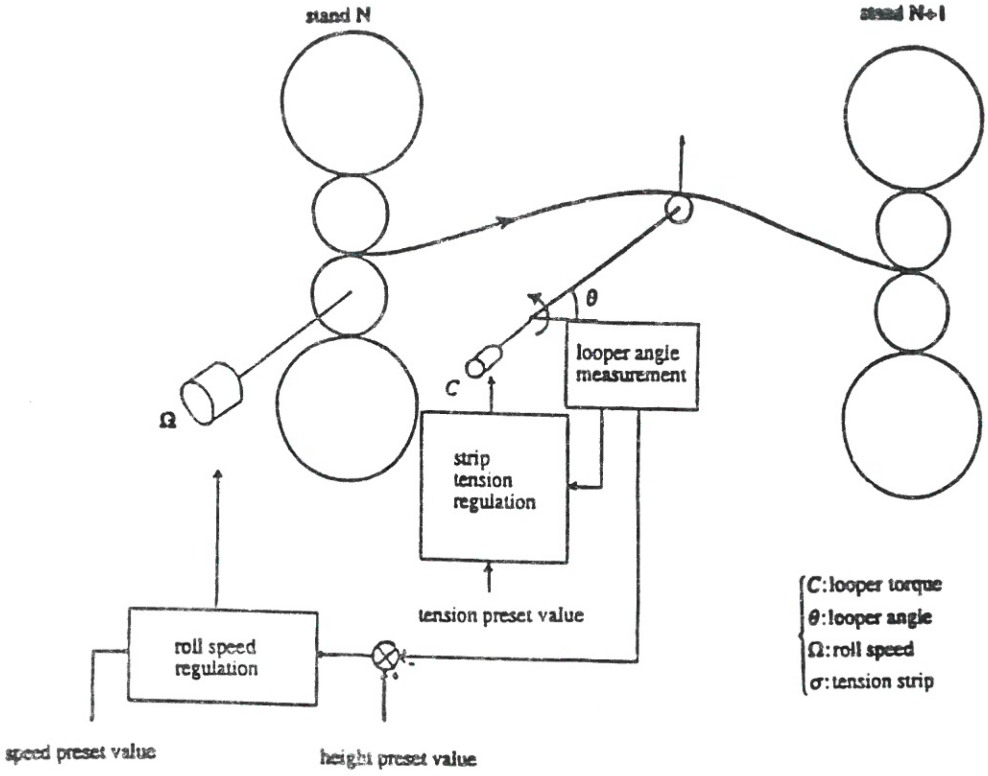


Figure 1.Working Principle of Finishing Mill Interstand

2. Conventional Control System

A representative type of conventional looper system is shown in the block diagram of Figure2.

In this Figure, the looper height is the controlled variable, and the looper height control system employs closed loop control, whereas the tension control system employs open loop control.

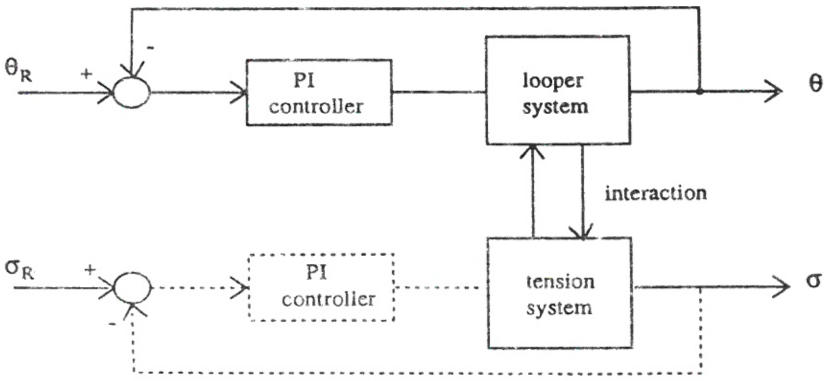
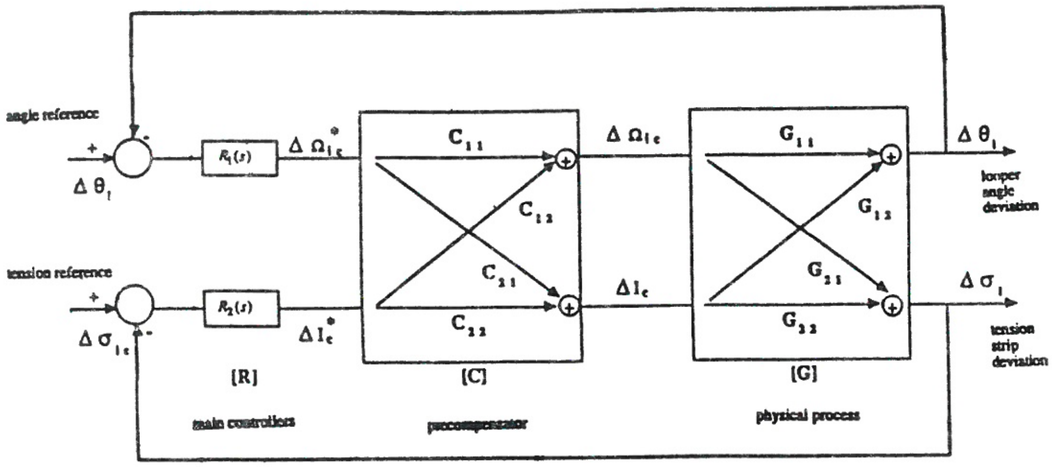


Figure 2. Conventional Control System



symbols : $\Delta\Omega_{ic}$: speed deviation of main motor

ΔI_c : current deviation of looper motor

Figure 3. Block Diagram of Decoupling Multivariable System

In this conventional system, tension is controlled indirectly by regulating the looper height and by maintaining constant the looper torque. To improve the control tension, we can also introduce a PI controller whose entry will be the difference between the measurement of strip tension and the tension preset value.

It was shown that skid mark disturbance in that case was strongly rejected in tension strip and so tension performance is obviously increased, which is very important for the improvement of accuracy of both thickness and width in a hot strip finishing mill.

Different criteria are used to optimize the regulators of the actual system [1] (Generalized Naslin Criterion, Gain Margin, Routh and Absolute Stability Margin Criteria, Hall and Sartorius Criterion) which enable perturbations to be rejected. A comparison of the results determines the final choice of a reliable criterion which provides the best response of looper angle and strip tension in the case where perturbations exist.

However, the mutual interaction between interstand strip tension and looper angle makes it difficult to control them satisfactorily.

In order to overcome this difficulty, a non-interactive control system employing cross controllers has been installed in the looper system. There, the application of decoupling multivariable control using a state feedback controller, has been studied.

These new control systems will be described below.

3. Decoupling Control System

3.1 - Elimination of Interference in Looper System in Frequency Domain

Since interactions between the looper angle θ and the strip tension σ occur due to rolling phenomena, it is necessary to remove this mutual interference by introducing a cross controller of the precompensator type as shown in Figure 3 [2].

This way, the looper angle system and the strip tension system form two independent monovariable systems which are controlled by separate proportional integral (PI) controllers.

The precompensation matrix $C(s)$ is selected so that the transfer function matrix $F(s) = G(s) \cdot C(s)$ is diagonal : $F(s) = \begin{pmatrix} F_1(s) & 0 \\ 0 & F_4(s) \end{pmatrix}$ where $F_1(s)$ and $F_4(s)$ are respectively the transfer function of looper angle and strip tension equivalent monovariable system. Their dynamics responds to the required performance; the time responses of $F_1(s)$ and $F_4(s)$ are chosen in compatibility with the open loops of work roll speed regulation and looper motor torque regulation, respectively.

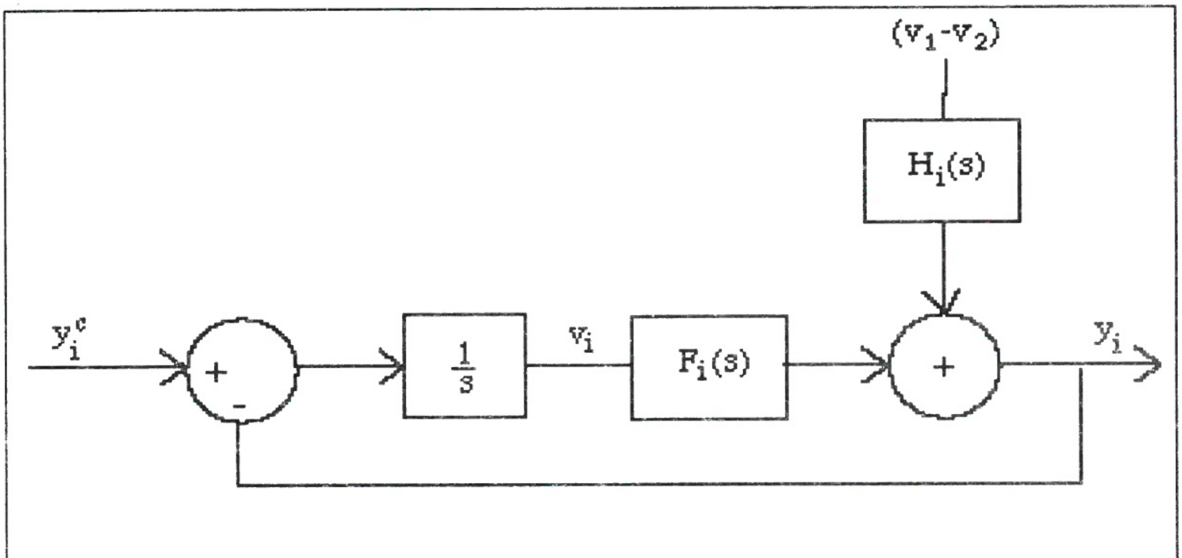


Figure 4. Block Diagram of Decoupled Sub-system on Closed Loop

The choice of Naslin characteristic ratios all equal to 2 for $F_1(s)$ and $F_4(s)$ permits to have a correct damping of the angle looper and tension strip responses.

$R_1(s)$ and $R_2(s)$ are then optimized in order to minimize the effects of perturbations on looper angle and strip tension, and consequently to increase strip dimensional accuracy and ensure a more stable operation of the finishing mill.

3.2 Elimination of Interference in Looper System in State Space

The looper system can also be represented in the state space by the following state equations :

$$\begin{cases} \dot{x} = Ax + Bu + Hz, \\ y = Cx, \end{cases} \tag{1}$$

where A, B, C and H : the index matrices ;

$u \overset{\Delta}{=} \left[\Delta\Omega_{ic}, \Delta I_c\right]^T$: the input vector ;

$y \overset{\Delta}{=} \left[\Delta\theta_i, \Delta\sigma_i\right]^T$: the output vector ;

x : the state vector ;

z : the disturbance vector.

The following control law is proposed for assigning the open loop dynamics of the decoupling system,

$$u = Kx + L(Dv - w), \tag{2}$$

where D is a diagonal matrix : $D = \operatorname{diag}(\mu_i) \quad 1 = 1 \ldots m$, w is a column vector, a combination of the output and its successive derivatives, so it can also be written as $w = Mx$.

K, L are decoupling matrices so that each output y_i depends only on the input v_i [3].

To reject constant disturbances on output, it is necessary to place an integral controller in the direct chain of each decoupling subsystem, as shown in Figure 4.

$F_i(s)$: transfer function of decoupling system in open loop,

$H_i(s)$: transfer function of perturbations.

The matrices D and M are adjusted so that the transfer function on closed loop, linking the output y_i to the reference value y_i^c, has the following characteristics :

a) a time response compatible with the required dynamics ;

b) a satisfying damping factor defined by the choice of Naslin coefficients all equal to 2.

This control law applied to the latter finishing mill interstand distinctly improves the looper angle and the strip tension response; the examination of these results will be made in the following section.

4. Optimal Control System

4.1 Synthesis of Looper Optimal Multivariable Control

An integral-type optimal regulator is included as an additional integral term to eliminate the steady-state error between the controller variable and the reference value [4]. The manipulated vector of the looper system is obtained by adding the state feedback vector to the main controller output vector, that is, the manipulated vector u is given by:

$$u = K_I \int_{t_0}^{t} (y_R - y)dt + Fx + u(t_0),$$

where K_I is the main controller gain matrix, F is the state feedback gain matrix, y_R is the reference value vector, $u(t_0)$ is the manipulated vector at $t = t_0$, and t is the time.

The control system configuration is given in Figure 5.

The controllers K_I and F are obtained to minimize the quadratic performance index J in equation (3). The weighting matrices $Q(\geq 0)$ and $R(> 0)$ are constant square matrices chosen to determine the control performance index.

$$J = \int_0^{\infty} \left(x_d^T Q x_d + u_d^T R u_d\right)dt, \tag{3}$$

where

$$x_d = \left[(y_R - y)T, (dx/dt)^T\right]^T, \tag{4a}$$

$$u_d = du/dt. \tag{4b}$$

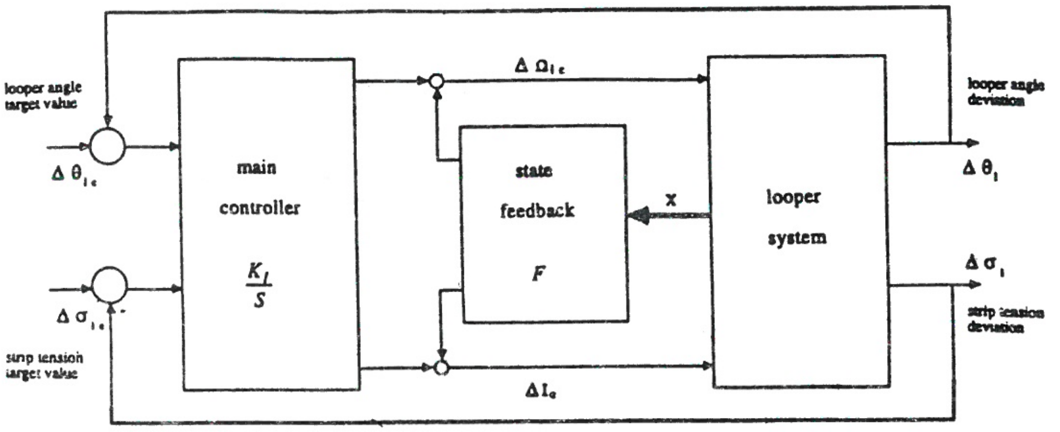
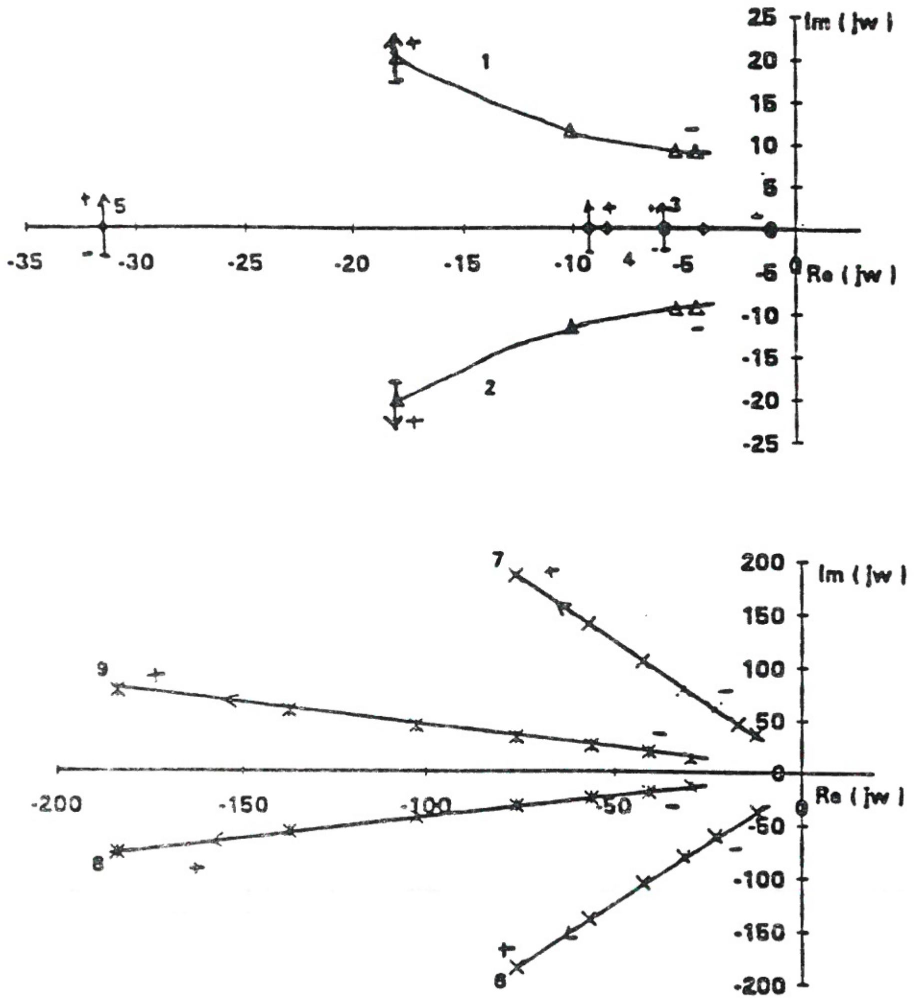


Figure 5. Block Diagram of Optimal Multivariable Control

4.2 - Selection of Weight Matrices

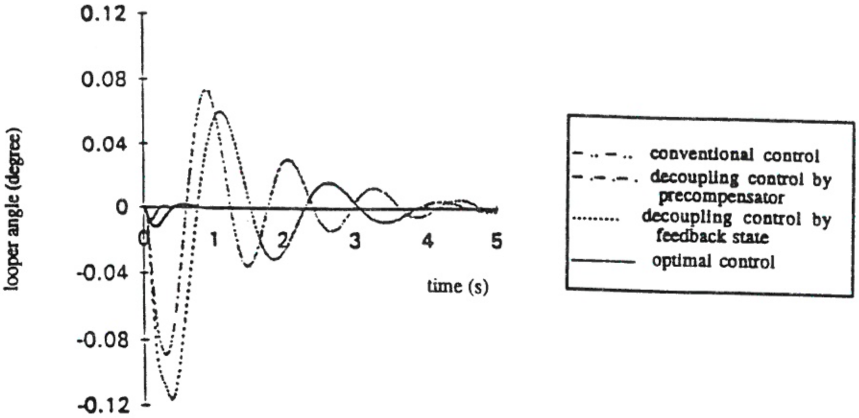
The performance index J in equation (3) is normalized by using adimensional variables. This normalized formulation brings in weighting coefficients that are adjusted by simulation until obtaining the desired performances.

At first, the change in the pole position on adjustment of each weighting coefficient was investigated, giving a general idea of the speed of transitory behaviour. A sample of calculation results is given in Figure 6. The change in coefficient β_1 (related weighting strip tension error - looper angle error) was set at 10^{-3} to 10^3.

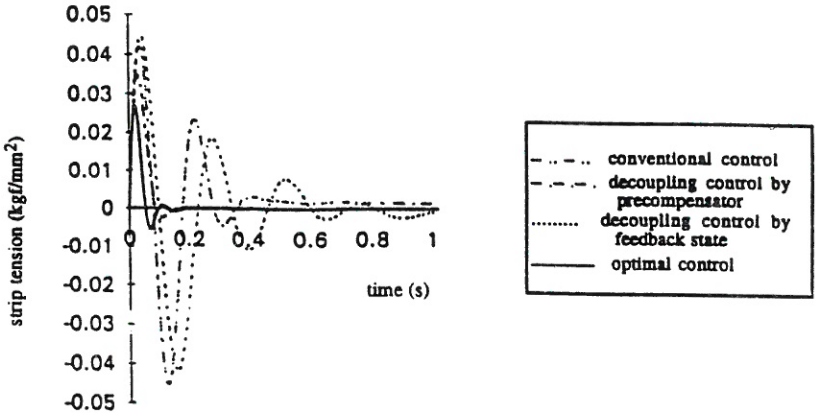


Legend :
1 , 2 , 3 ... : pole number
▲ ● ◆ , ... : pole symbol
(the same for conjugated poles)
↑ : invariant pole
→ : displacement direction of the pole for increasing value of β_1

Figure 6. Pole Positions Change As Functions of the Weighting Coefficient β_1

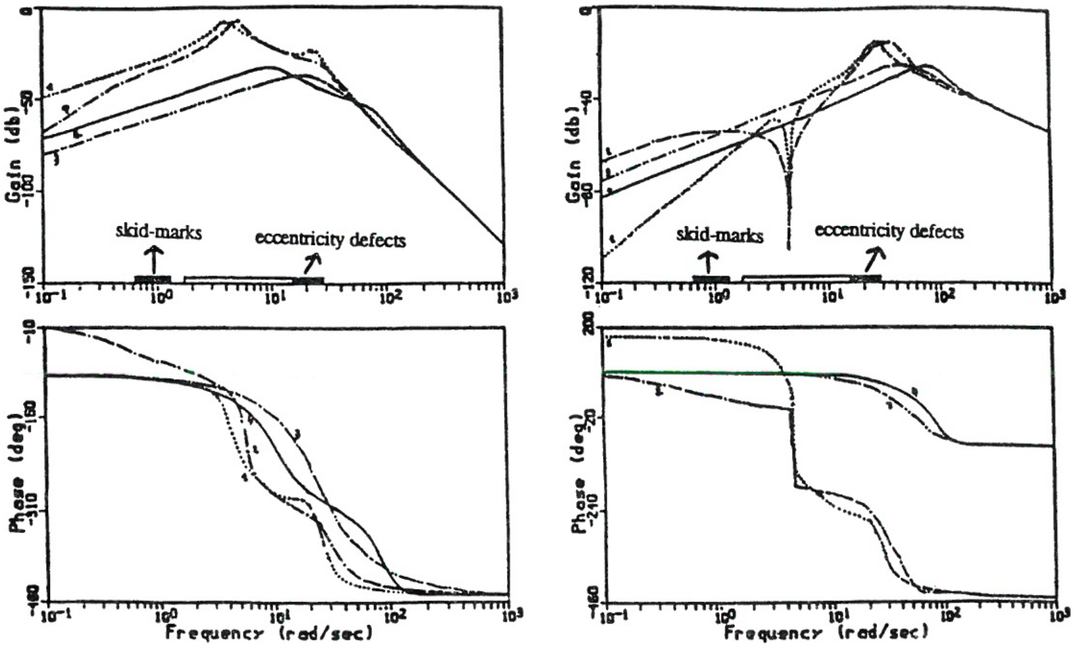


(a) Looper angle step response.



(b) Strip tension step response.

Figure 7. Simulation Results of Temporal Responses for Different Control Systems



(a) Bode diagram of $\Delta\theta_i / (v_1 - v_2)$

(b) Bode diagram of $\Delta\sigma_i / (v_1 - v_2)$

1 : Conventional control
2 : Decoupling control by precompensator
3 : Decoupling control by state feedback
4 : Optimal control

Figure 8. Simulation Results of Frequency Responses of Different Control Systems

The example of Figure 6 shows that an increase in the weighting coefficient β_1 greatly affects the pole positions, and ensures a better stability margin of the system. Nevertheless, the latter is limited by the value of β_1 equal to 1 since the dominant poles (1 to 5) become invariant.

Furthermore, the variation of each weighting coefficient enables to quantify the impact on temporal performances such as time response and overshoot. Finally, simulations give an order of magnitude of actuators solicitations, depending on weighting parameters.

5. Simulation

The new controls of an interstand hot strip finishing mill are compared with the conventional control system by simulation. Such a comparison can be carried out with two types of response : step response (e.g. for a step input) or frequency response (Bode diagrams).

5.1 Temporal Response

Simulations of the step response of the looper angle and strip tension to a mass-flow disturbance step $(v_1 - v_2)$ (Figure 7) have been carried out for different controls of the last finishing interstand, in order to evaluate the control performance.

It can be seen that the new control systems by state feedback (decoupling control, optimal control) perform better than the conventional control system in term of both the looper angle and strip tension. Figure 7 clearly shows that the stabilization time and the rejection amplitude of these disturbances, in that case, are very reduced if compared with conventional controls.

5.2 Frequency Response

Frequency responses between mass-flow disturbance and looper angle and strip tension are shown in Figure 8. It can be seen that with an optimal control system, the effect of disturbance on strip tension is considerably lower than with the conventional one in a large frequency domain, while the latter is appropriate for eliminating disturbance only in the frequency range of 0 to 2 rad/s where there are skid marks. In addition, the disturbances are well rejected on looper angle, especially in the case of control systems by state feedback.

6. Conclusion

Different controls of a hot strip finishing mill interstand have been studied to improve the disturbance control capability. The efficiency of the design techniques has been proved by simulation. The results of this study can be summarized as follows :

- the multivariable control systems by state feedback are effective in increasing the stability of strip tension and looper angle in the presence of large disturbances occurring during the rolling of strips ;
- the optimal control system permits to observe the actual saturation thresholds of actuators, and guarantees better robust stability of the whole system.

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