

## Design of Rolling State Observers for Application to Control of Thickness and Tension in Rolling Mills

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**Abstract:** This study focuses on the necessity of designing state observers to be used in controller synthesis for rolling processes. This is motivated by the fact that using several kinds of sensors for measuring all of process variables is technically and economically avoided. On the other hand, using exact measurement in feedback control systems could considerably improve the quality of products. In other word, there is a trade-off between high quality and the implementation limitations, managed here by developing rolling state observers. The proposed observers estimate the states not measured directly by the installed sensors. This technique is applicable to both hot rolling and cold rolling processes. Simulation results demonstrate the performance of the proposed estimation algorithm.

**Key words:** Estimation error, feedback control, mathematical model, rolling mill, state observer

### INTRODUCTION

Rolling mill productions have an important role in various applications as automotive industries, home appliance, and manufacturing. The quality of productions in rolling processes is evaluated by many factors as flatness, exact thickness, desired elasticity and so on (Ginzburg, 1993). Achieving flat sheet with high quality is possible provided that an effective control strategy is adopted.

Although many control algorithms may theoretically meet such desired properties, but some practical limitations cause those methods not be implementable. In fact, rolling mills are some nonlinear systems with multiple inputs and multiple outputs (Kugi and Navak, 2000; Murakami *et al.*, 2002; Tezuka *et al.*, 2002). Apart from the mechanical equipments, a big potential for improving the quality of the rolled products lies in the techniques adopted for process control. Meanwhile, high quality can be obtained by some control algorithms at the expense of using many sensors and actuators which may be not cost effective. Therefore, the trade-off between high quality and economical or technical limitation should be managed in such a manner that the best result is achieved.

Tension and speed control of the continuous strip processing lines are the challenging problems to be devoted to get high performance. During the past years, various control methodologies have been developed for hot or cold rolling processes under different assumptions (Kadoya *et al.*, 1999; Song and Sul, 2000; Janabi-sharifi,

2005; Chen and Huang, 2010). The so-called BISRA (British Iron and Steel Research Association), AGC method, based on the gaugemeter principle, has been widely used in steel rolling mills (Ginzburg, 1993). However, these AGC methods are very sensitive to the mill modulus and thus, control performance is deteriorated if modeling error exists in the mill modulus. Besides, using several sensors for measuring different parameters is inevitable. Inverse Linear Quadratic (ILQ) theory, as a multivariable and optimal control technique can be applied to mass flow thickness control in rolling processes (Imanari *et al.*, 1998; Kadoya *et al.*, 1999). As it is straightforward to design control systems based on ILQ theory and it is easy to tune the resulting system, this method is often used for actual plant control.

In general, two kinds of tension control schemes may be used in the industry (Song and Sul, 2000). One is feedback control technique based on the direct detection of tension with load cells and the other approach is the indirect calculation of required motor torque from tension reference and radius. Each of the aforementioned methods suffers from some drawbacks e.g., they may be applicable in the case of the same roll radius and moment of inertia and other special cases.

In this study, the state observer design procedure is presented to be used in feedback control algorithms. In fact, using the estimate values, thickness and tension controllers can be developed without any extra sensors. Numerical analysis and various demonstrations are also provided to show the performance of the designed observer.

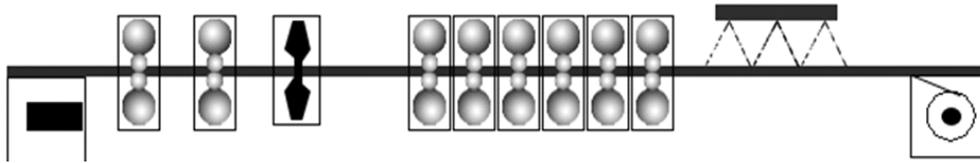


Fig.1: The schematic of a typical rolling mill process

Table 1: Symbol description

Symbol	Description
$h$	Exit thickness
$H$	Entry thickness
$r$	Thickness reduction
$V_R$	Roll velocity
$v$	Strip velocity
$R$	Work roll radius
$W$	Strip width
$s$	Yield stress
$f$	Forward slip
$S$	Roll gap
$K$	Elastic constant
$\mu$	Coefficient of friction
$P$	Roll force
$\sigma$	Tension

## MATERIALS AND METHODS

Rolling process plays an important role in steel manufacturing due to its versatility, efficiency and high production rate. Nowadays, the demand for rolled products with high quality in aircrafts, automobile, and other related industries has been extensively increased. The analysis of rolling process is divided into two distinct topics including hot rolling and cold rolling described in the sequel. A hot rolling mill transforms ingoing steel slabs into flat strip by reducing the thickness of the slabs, from about 200 mm to a thickness of below 5 mm. The schematic of a typical hot rolling mill is shown in Fig. 1. Thickness reduction is managed by several coupled stands, each consists of two work rolls and backup rolls. In fact, the slab is passed through 7-9 rolling stands and the thickness is reduced gradually. In order to change the stiffness of the rolled products, to be usable in industry, a considerable attention is paid to cold rolling process. Moreover, by tandem cold mills large reductions can be achieved with relatively close tolerance on flatness and thickness of about 1 mm.

In the rolling process, strip is passed through a continuous production line, from one mill station to another, at high speed. In general, the fundamental equations govern the process are nonlinear but setting the mill for an operation point, one can linearize the model (Kadoya *et al.*, 1999; Murakami *et al.*, 2002). The model is derived using influence coefficients and various equations such as exit strip speed, rolling force, motor current based on rolling theories (Ginzburg, 1993). The basic equations which establish the relationship among the variables are formed by the characteristics of the

material and the mechanical variables e.g., tension and forces. In the following, presenting the equations of rolling processes and numerical study are mainly performed based on those of Mobarakeh Steel Company, Isfahan, Iran. Table 1 describes the symbols that appear in the equations.

The rolling force equation for the  $i$ th stand is given by Asano and Morari (1998):

$$F_i(H_1, H_i, h_i, \sigma_{fi}) = 0 \quad (1)$$

where;  $H_1$  is the entry thickness of the first stand, and  $h_i$ ,  $H_i$ , and  $\sigma_{fi}$  denotes respectively the exit thickness, the entry thickness and the tension at front of the  $i$ th stand. The exit strip thickness is governed by:

$$h_i = S_i + F_i/k \quad (2)$$

in which  $S$  represents the roll gap and  $K$  is the elastic coefficient. The dynamic behavior of rolling mills is mostly determined by:

$$\dot{S}_i = 1/T_s(S_i - U_{si}) \quad (3)$$

and

$$\dot{v}_{Ri} = -\frac{1}{T_v}(V_{Ri} - U_{vi}) \quad (4)$$

where,  $U_{si}$  and  $U_{vi}$  are the reference values and,  $T_s$  and  $T_v$  are the related time constants, and

$$\dot{\sigma}_{fi} = \frac{E}{L}(v_{b(i+1)} - v_{fi}) \quad (5)$$

In fact, Eq. (3)-(5) represent the dynamics of roll gap, roll velocity  $V_R$ , and tension at each stand respectively. In (5),  $E$  is the Young's modulus and  $L$  is the distance between each two stands.

In general, the dynamic behavior of the process represents nonlinearities. Although the relationships between some of the process variables are nonlinear, but at steady state the equations governing the system would be linear (Imanari *et al.*, 1998; Murakami *et al.*, 2002;

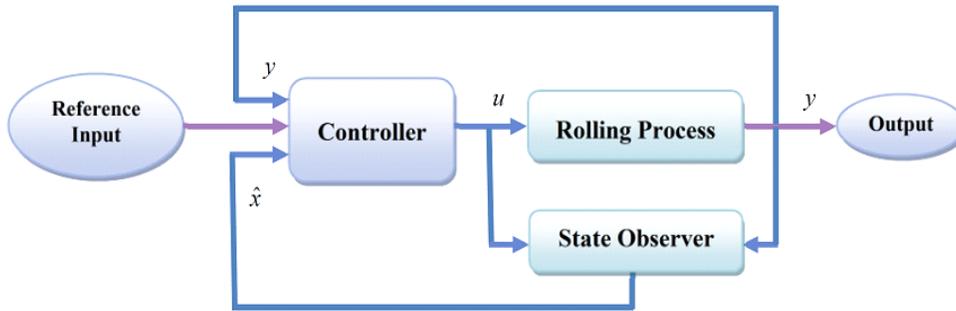


Fig. 2: Feedback control based on state estimation

Tezuka *et al.*, 2002). The linearized model around the operating point presents a state-space description of the form:

$$\begin{cases} \dot{X} = AX + Bu \\ y = CX \end{cases} \quad (6)$$

where,  $X$ ,  $y$  and  $u$  denote the vectors of states, outputs and inputs respectively. Moreover  $A$ ,  $B$ ,  $C$ , are some matrices with appropriate dimensions. More precisely,  $X$  contains the interstand tensions, roll velocities and gap between work rolls, i.e., for  $n$  stands one can select:

$$X = [\sigma_{f1}, \dots, \sigma_{fn}, V_{Rn}, S_1, \dots, S_n]^T \quad (7)$$

The dimension of state vector  $X$  depends on the number of stands in rolling mill. The model description (6) can be adopted in many advanced control techniques provided that the whole states are measurable.

In practice, measuring the whole variables may be possible at the expense of using many sensors. Hence, designing a feedback control system which uses the estimated value of some unnecessary states is highly desired. To this end, developing a state observer is taken into account as a preliminary step to construct such a controller.

## RESULTS AND DISCUSSION

Figure 2 demonstrates the estimation-based control strategy for rolling mills. Specifying the parameter values in each rolling process, the numerical values of  $A$ ,  $B$ ,  $C$ , is obtained and state space model of the process is determined. The state observer is designed based on the Lyapunov equation (Chen, 1998).

As a preliminary step to design such an observer, put the states which must be estimated in a vector as  $z$ . Now the estimation algorithm can be developed by the following steps. Consider the observer equation as:

$$\dot{z} = Fz + Gy + Hu \quad (8)$$

where,  $F$  is selected by designer to be a Hurwitz matrix without any common eigenvalue with matrix  $A$ . Meanwhile, the vector  $G$  is determined such that  $(F, G)$  is controllable. In Eq. (8),  $H$  is calculated by:

$$H = TB \quad (9)$$

where,  $T$  is obtained by solving the matrix equation:

$$FT - TA = -GC \quad (10)$$

Therefore, Eq. (8) can be solved and vector  $z$  presents a mapping of the state estimation vector  $X$  and yields:

$$\hat{X} = T^{-1}z \quad (11)$$

So the state observer, depicted in Fig. 2, can be implemented. Now, the performance of the proposed estimation algorithm is evaluated via illustrative simulations. To this end, consider a typical cold rolling mill with two stands introduced by Kugi and Navak (2000). The state vector of such rolling process, aimed to estimate, is  $X = [\sigma_p, V_{R1}, S_1, S_2]$ . Calculating the state-space matrices, one can follow the design procedure formed by (8)-(11). In order to evaluate the estimation algorithm, define the error vector  $E = X - \hat{X}$ .

The time responses of the normalized estimated values of states, demonstrated in Fig. 3, show the convergence property of the proposed estimation

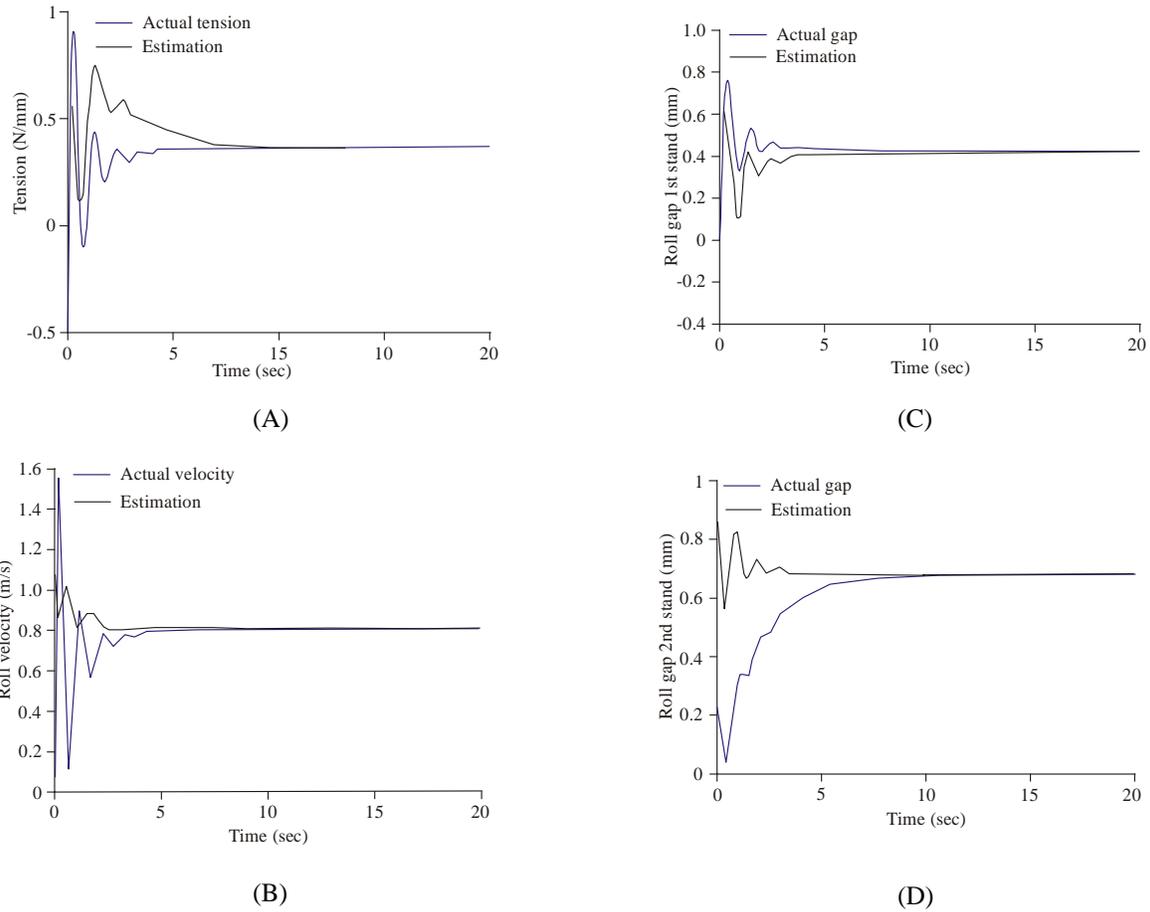


Fig. 3: The convergence of normalized estimated signals, (a) interstand tension  $\sigma_p$ , (b) roll velocity  $V_{R1}$ , (c) roll gap  $S_1$ , (d) roll gap  $S_2$

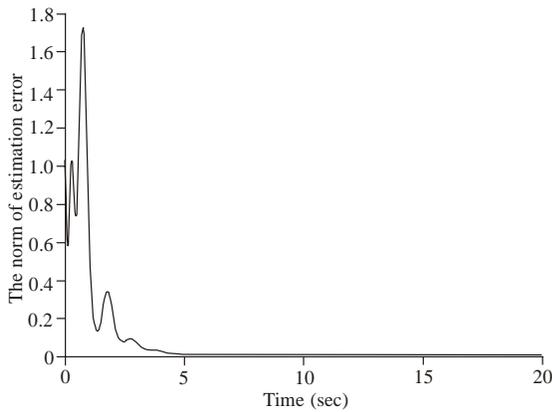


Fig. 4: The norm of estimation error  $\|E\|$

algorithm. Meanwhile, Fig. 4 shows that the norm of estimation error vector  $E$  is converged to zero.

## CONCLUSION

The dynamical behaviors of hot rolling and cold rolling mills are briefly discussed. The mathematical model of rolling mills shows that a linear model can be derived to be used in process analysis and control in a specified operating condition. A state space description is adopted for the process and developing an estimation algorithm is focused. The state observer provides the system with using the estimated values for some parameters instead of measurement. This strategy removes the demand on using several sensors which may be technically or economically not possible.

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