# A SURVEY OF THE LOOPER-TENSION CONTROL TECHNOLOGY IN HOT ROLLING MILLS

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Abstract: Looper and tension control is important in hot strip mills because it affects the strip quality as well as strip threading. Moreover, the most difficult challange in the controller design and control performance comes from the interaction between looper angle and strip tension. Disturbances from several sources also cause a deterioration in control performance, and thus they should be rejected effectively by proper control algorithms. Up to now, various kinds of control schemes have been proposed and applied to this control problem. Recently nevertheless, strict demand for strip quality by the market has required improved approaches to this control area. This paper investigates strong and weak points of various control algorithms proposed in academia as well as industry. It also explores the potential of future technology in this area. 

Keywords: Conventional PI control, Observer–based Control, Internal Model Control, $H_\infty$ Control, Model Predictive Control

## 1. INTRODUCTION

There are two major specifications which should be satisfied in hot rolling mills; these are the dimensional quality and mass flow of the strip. The dimensional quality specification includes the thickness, width, flatness and profile of the strip. Control is performed by dedicated control systems such as AGC (Automatic Gauge Control), AWC (Automatic Width Control), ASC (Automatic Shape Control) and APC (Automatic Profile Control). Mass flow control is used to balance the input and output flow of a strip in a stand. It enables smooth threading of a strip and stable operation of the process. Control is used to change the stored loop length between stands by manipulating a mill motor speed; looper angle control is used in conventional schemes whereas strip tension control is used in advanced control schemes.

Strip tension control is important because it affects both the dimensional quality and the mass flow of a strip. For example, high tension induces width shrinkage, thickness reduction and can produce an edge wave on a strip but it does make the mass flow more stable. Hence the use of strip tension produces a tradeoff between dimensional quality and mass flow. Therefore, tension should be kept to a desired value during operation to ensure proper product quality and threading.

A looper installed at inter–stand positions reduces tension variations by changing its angle, so it can contribute to the quality of products. It can also enable stable operation of the process by absorbing an excessive loop of the strip arising

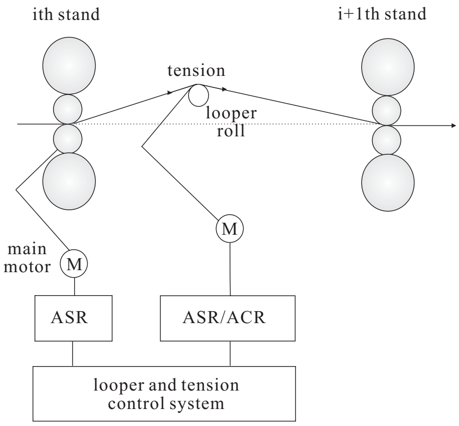


Fig. 1. Tension and looper control in finishing mills
Where, ASR: Automatic Speed Regulator, ACR: Automatic Current Regulator

from mass flow unbalance. For example, in the case of low tension, the looper angle increases to get proper tension, resulting in the stable threading of a strip, while, in the case of high tension, the looper angle decreases to reduce strip tension. Ideally, the looper angle needs to keep a desired value during operation to reduce the tension variation and to have the flexibility to achieve large changes in loop length during an abnormal rolling condition.

Thus, the specifications of dimensional quality and mass flow in hot rolling mills can be satisfied by proper control of the strip tension and looper angle. Figure 1 shows the tension and looper control in a typical finishing mill.

Traditionally, looper angle control has been performed by changing the rotating speed of a main motor but there has been no tension feedback control because of the difficulty of installing and maintaining tension meters at inter–stand positions. Conventional PI control has been used most widely in industry; this is described in section 3. The main advantage of this looper control scheme is that it does not use tension meters, and hence it is easy to design a controller as this reduces to a SISO system. On the other hand however, there is significant interaction between the tension and looper angle, which degrades the control performance and stability and the SISO loop does not tackle this. Various research papers seeking to improve the performance and stability of this scheme have been published, for instance, (Schuurmans and Jones (2002), Asada et al. (2003), Janabi-Sharifi (2004)).

The main weakness of looper angle control is the 'neglect' of the interaction. Hence using recent advances in the technology of sensor applications, there has been an increased installation of tension meters. Hong et al. (2001) developed a tension meter using load cells and applied it to width control problems whereas some approaches suggested the use of soft sensor based on estimation theory to control strip tension (Hearns and Grimble (2000a)). The availability of tension measurements has enabled tension feedback and the reduction of interaction by changing control pairings such that the rotating speed of a mill motor controls strip tension while angular velocity of a looper motor controls looper angle. Using this scheme makes the process model a two–input and two–ouput multivariable system, and many advanced control algorithms based on this control structure have been applied and shown to give improved control performance (Imanari et al. (1997), Hesketh et al. (1998), Asano et al. (2000)). Nevertheless, recently more and more strict demand for strip quality in hot strip mills by the market has required yet further advances to the control approaches in this area.

This paper gives a survey of the strong and weak points of the various control algorithms proposed in academia as well as those implemented in industry. It also explores some future technology in this area. The control problem is described in section 2, a survey of looper–tension control technology is discussed in section 3, future technology for looper-tension control is explored in section 4 and conclusions are given in section 5.

## 2. CONTROL PROBLEMS

This section gives an overview of the tension and looper model, the control issues caused by disturbances and the controller specifications.

### *2.1 Tension and looper model*

Inter–stand strip tension is defined by the stretch and Young's modulus $E$ of the strip (see fig. 2) as follows:

$$\sigma(t) = E[\frac{L^{'}(\theta(t)) - L(t)}{L(t)}] \tag{1}$$

$L^{'}(\theta(t)) = \sqrt{(x^2+y^2)} + \sqrt{(L_0-x)^2+y^2}$ and $L = L_0 - \int_0^t (v_{in,i+1} - v_{out,i})dt$. A looper motor can control loop length $L^{'}$, while $L$ is changed by the main motors.

The looper model is derived by applying Newton's second law with an inertia $J_L$, motor torque $M$ and load torque $T$.

$$J_L\ddot{\theta} = M - T \tag{2}$$

Load torque $T$ includes the torque by strip tension, the torque from strip and looper weight,

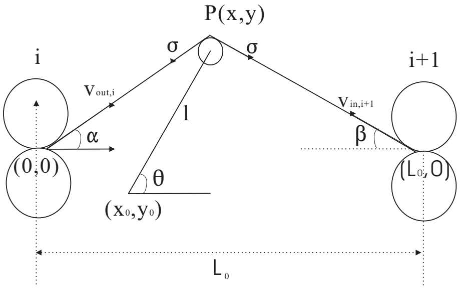


Fig. 2. Outline of a looper

the torque to bend the strip and the frictional damping torque.

The strip tension in eqn. (1) depends on loop length $L'$ which is determined by looper angle, while the looper angle is affected by the strip tension in eqn. (2). Therefore there is an interaction between the looper angle and strip tension. This interaction makes it difficult to design a controller and the obvious consequence is degraded control performance and stability.

### *2.2 Disturbance*

There are tension disturbances from several sources which affect both control performance and stability.

The main disturbance comes from the AGC action. AGC systems are there to get higher gauge quality; they reject thickness disturbance due to set–up mismatch, skid marks, roll eccentricity and so on. However, while the hydraulic screw down system makes it possible to give quicker response to the AGC, it often creates a disturbance to the tension control system because of the mass flow change caused by roll gap movement.

Another disturbance comes from the set–up mismatch. Before the strip arrives at the finishing mill, a supervisory computer calculates initial set–up values such as the roll gap and rolling speed for the stands to get required specifications. However, the mismatch between the real processed values and set–up values creates a constant disturbance in the tension and thickness.

Another disturbance occurs for downstream loopers at coiling (Imanari et al. (1997)). When the lead end of a strip is coiled, a large tension between the last stand and a down coiler is often caused. This can cause tension fluctuations at the finishing mill inter–stand.

All these disturbances influence the strip tension and looper angle control performance, thus affecting strip thickness, width, flatness and mass flow.

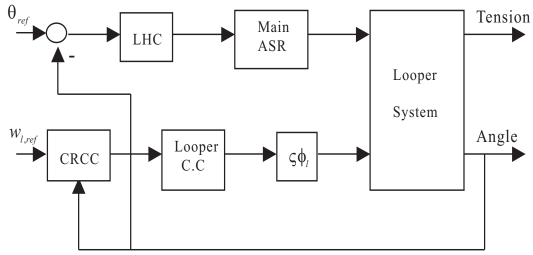


Fig. 3. Conventional PI control Scheme
Where, C.C: Current Controller

### *2.3 Specifications for Controller design*

The objective of the looper and tension controller is to maintain the tension and looper angle at their desired values regardless of disturbances and interactions. Many controllers have been designed to satisfy the following design specifications.

- Stability of the closed loop system is guaranteed under parameter uncertainties and disturbances.
- Responses of the tension and looper angle are as quick as possible.
- The interaction effects are minimised.
- Tension control performance is more important than looper angle performance.
- The effect of disturbances is suppressed as much and as quickly as possible.

## 3. SURVEY OF LOOPER–TENSION CONTROL TECHNOLOGY

Some algorithms have been applied successfully in industry. This section describes some examples of more recent technologies used for looper–tension control and also a more conventional control PI scheme.

### *3.1 The Conventional PI Control Scheme*

A conventional control scheme has been used most widely in industry because of its simplicity and besides, it doesn't need tension meters. Fig. 3 shows the block diagram of a conventional controller (POSCO and HITACHI (1997)). In this scheme the torque of the looper motor is adjusted according to looper angle to maintain strip tension to a desired value. The CRCC (Current Reference Calculation Controller) computes the reference current to balance the torque on a looper motor against the load torque at the given angle which depends on the strip tension, strip weight, looper weight and so on. Fig. 4 represents the details of a CRCC block.

The mass flow in this control scheme is controlled by the looper height control (LHC) loop which

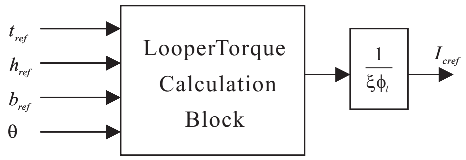


Fig. 4. A block diagram of CRCC
Where, $t_{ref}$: tension reference $[N/mm^2]$, $h_{ref}$: thickness reference$[mm]$, $b_{ref}$: width reference $[mm]$, $\theta$: actual looper angle $[rad]$, $\xi\phi_l$: current torque coefficient of a looper motor $[Nmm/A]$, $I_{cref}$: reference current of a looper motor $[A]$

changes the inter–stand strip length by the rotating speed of a mill motor. The LHC performs PI (Proportional and Integral) control action to get rid of the angle difference between the target and measured looper angle. The control mechanism is explained as follows. In steady state, the load torque including the strip tension balances the torque supplied by a looper motor, so the looper angle is stationary. However, if the strip tension is increased by a disturbance, then the load torque becomes bigger than looper motor torque, so the looper angle decreases. When the decreased angle is detected, the LHC increases the rotating speed of an upstream main motor to recover the looper position. The main problem of this scheme is a interaction between the looper angle and strip tension resulting in slow response and large deviations in the tension and looper angle. If the controller gain is chosen to be bigger in order to improve the control performance, the plant will become unstable due to the interaction.

### *3.2 Robust–Adaptive Looper Control*

Asada et al. (2003) suggested the use of robust and adaptive control of the looper to assure stability and to improve control accuracy of angle. The change of the material characteristics and the slip between roll and strip may make the conventional looper control systems unstable. To overcome this problem a robust controller was designed based on the internal model control. In designing the controller the filter $F(s)$ is designed to be small for the frequencies of low damping coefficient to maintain robust stability, while for all frequencies a conventional robust controller is designed ( Fujisaki et al. (1990)). Therefore, this scheme requires the estimation of the damping coefficient, which can enables the adpative changes to the control gains. Moreover, in order to reduce the influence of the disturbance, the filter was designed such that the sensitivity function $S(s)$ is small at low frequencies. The resultant controller ensured both the robustness and high control performance of looper angle regardless of the changes in the rolling conditions and disturbances. The main contribution therefore was to give a control scheme which stablised the looper control sytem under changes of operation condition by utilizing a robust controller. Moreover, it also solved the problem of the slow response of conventional robust design by incorporating adaptive control through an estimation of a looper parameter. However, the weakness was that angle control accuracy depends on the estimation error and there are still performance limitations due to the use of a SISO system design.

### *3.3 Observer–based Control*

Hoshino et al. (1996) developed an observer–based tension control and applied it to aluminium hot rolling mills. Their approach used control pairings such that the changing rolling speed of the upper stand controls strip tension while torque of a looper motor controls looper angle. State feedback control was designed and implemented using analytical process models, and disturbance observation of tension and looper torque. They achieved offset free tracking under constant disturbances by giving additional control inputs to counter balance the disturbances in steady state. The key advantage of this scheme is that it is easy to tune the controller thanks to the analytical derivation of the control parameters. However, because there is no systematic handling of interactions it can give violent torque fluctuations in the case of a large initial tension disturbance. Such an event may be followed by instability of the process at strip threading time. This problem was solved in an ad–hoc manner by setting the looper angle response slower than the tension response.

### *3.4 Internal Model Control + Impedance Control*

Asano et al. (2000) developed a tension and looper control scheme based on decentralization and coordination. They chose the manipulated variables as the rotation speed of a main motor for tension control and the angular velocity of a looper motor for angle control and achieved reduced interaction effects. This was verified by an interaction measurement using singular values, which demonstrated the validity of designing two decentralised controllers. The controller was designed based on the two–degree–of–freedom IMC (Internal Model Control) structure with reference tracking and low frequency disturbance rejection. However, the designed control scheme weakened the coordinated action of the looper; the looper control loop tried to keep the looper angle constant regardless of tension variation. Therefore, in order to improve transitional responses they incorporated an impedance controller which includes the looper model to calculate the desired looper position in accordance with tension variations. The main advantages of this control scheme are;

- It is easy to design the controllers because this scheme consists of two SISO (Single Input and Single Output) subsystems.
- It enables stepwise commissioning of control systems by adding control modules such as the IMC and impedance control to PI controllers.
- On–line tuning can be done intuitively because the controller parameters allow physical interpretations such as a disturbance observer and mechanical impedance.

However, for effective interaction reduction this control scheme depends only on the process model and so the ignored interaction, that is the off–diagonal elements of the process, can imply significant restrictions on the controller gains.

### *3.5 $H_\infty$ Control*

Imanari et al. (1997) developed a robust controller for the tension and looper control system. For controller design the weighting functions were chosen to let the sensitivity function be small in low frequencies to ensure a good disturbance rejection ability whilst letting the complementary sensitivity function be small at high frequencies to reduce the effects of noise and plant uncertainty. They adopted a state–feedback–type controller instead of output–feedback–type because it has lower order and doesn't imply pole–zero cancellation. The designed controller satisfied the requirements for both stability and disturbance rejection. However the tension control performance wasn't satisfactory compared with angle control. Therefore to improve tension control performance they introduced a cross parameter $C_1$ which enables the designer to change the angle reference to share the tension control. The major advantages of this control scheme are its ability to reject low frequency disturbance such as skid marks, to ensure robust stability for noise and model uncertainty, and to coordinate the tension control by moving the angle reference. However, the main disadvantage is the complexity of the controller, accompanied by the difficulty of tuning. Moreover, the incorporation of the cross parameter $C_1$ seems ad-hoc and needs to be designed in a systematic way.

### *3.6 Non–interactive Control + $H_\infty$ Control*

Shioya et al. (1995) proposed a non–interactive control for the tension and looper control with disturbance compensation. A conventional non–interactive control is used to design two independent PI controllers, with cross gains to compensate for the interaction effects (Kotera and Watanabe (1981)). Its advantages are the ease of controller design and adjustment, and the non–interactive characteristics between the tension and angle. However the scheme doesn't allow for high enough gains to reduce the disturbance driven variations in tension and angle sufficiently. Also it doesn't utilize the looper effectively because tension control depends only on the rotating speed of a mill motor. To overcome these disadvantages they incorporated a disturbance compensator into the conventional non–interactive control scheme. The disturbance compensator was designed by using a $H_\infty$ control design. In designing the compensator appropriate weighting functions were determined to reduce the disturbance effects in the low frequency and, to suppress the noise and modelling errors in the high frequency. The resultant scheme has independent controls with reference tracking by the non–interactive control and robust stability by the disturbance compensator. The advantage of the scheme is ease of controller tuning due to the independent controllers structure. The controllers can be adjusted as PI controllers for reference tracking, the cross controllers for interaction reduction and the disturbance compensator for disturbance rejection. However, robust stability has its limit in this scheme that means in order to increase robust stability, it is necessary to sacrifice the capacity of disturbance suppression. Moreover, the structure of controllers seems quite complex.

### *3.7 Optimal Control*

Seki et al. (1991) suggested a tension and looper control based on an integral–type optimal regulator. Two distinct controllers were synthesised using two set weighting matrices; one is controlled to have a minimum looper angle fluctuation within permissible tension range under normal operation condition and the other is designed for abnormal circumstances with a large tension fluctuation which exceeds the permissible range. The scheme controls the looper angle actively in order to return the tension fluctuation to within its permissible range quickly. This control is comprised of an integral controller, a state feedback controller and a control gain selector. It was implemented with programmable controllers and optical data links for high–speed data transmission. The advantage is the ability to get optimal performance by controlling the tension and looper angle simultaneously. Also cooperation of the looper to the tension control by changing the weighting matrix can improve the tension performance effectively under abnormal conditions. The disadvantage is the difficulty of implementation due to the control switching during operation. Moreover, the use of models with low orders to allow easy implementation can deteriorate the control performance.

Okada et al. (1998) proposed an optimal controller design method for an entire seven stands based on decoupling of the model. The model included the interactions among strip gauge, looper angle and strip tension for whole seven stands, and is decoupled by means of a similarity transformation. The decoupling enabled the treatment of the model as a set of units which do not affect each other. The optimal controller for each unit is designed by minimising the performance index of the unit depending on errors and controls and it is composed of state feedback gain, output feedback gain and similarity transfer matrices. The controller termed 'Local Autonomous Control' has some benefits because the finishing mill systems can be considered as a set of independent units.

- The solution of the Riccati equation can be calculated more easily.
- It is unnecessary to take account of the system's total optimality, but it is sufficient to select the weighting matrices so as to optimize each unit.
- Each unit's control system can start independently without considering the other units.

However, in this scheme the physical meaning of the states may not be preserved because of the state transformation for decoupling interacted–states.

### *3.8 Predictive control*

Recently, there have been some approaches to this area investigating the potential benefits of MPC (Model Predictive Conrol).

Schuurmans and Jones (2002) suggested an MPC controller for mass flow control design by taking account of constraints. They assumed constraint violation of output variables for difficult rolling material such as HSLA (High Strength Low Alloy) and took it into account in controller design. However, their design was applied to a SISO loop, looper angle control, and consequently some of the major benefits of the MPC for mutivariable system design such as interaction handling were not possible.

Choi et al. (2004) investigated the efficacy of an MPC scheme for looper-tension control problem using a MIMO model. They defined constraints on looper angle and strip tension to ensure quality specification and stable operation. The existance of large tension disturbances which cause constraint violations at abnormal operating conditions was assumed in the controller design. They designed a linear quadratic optimal MPC to ensure guaranteed stability and constraint satisfaction. The incorporation of integral action enabled offset free tracking under the disturbances. A comparison of the simulation results with PI control demonstrated that MPC control scheme can be a useful design strategy for looper-tension control problem in that it handles constraints as well as interaction systematically.

**Remark** *Some approches also use artificial intelligence (Jung and Im (1999), Janabi-Sharifi (2004)) because: (i) it does not require a formal model and (ii) it can use the considerable system knowledge of mill operators. However these are not discussed here.*

## 4. FUTURE TECHNOLOGY FOR LOOPER–TENSION CONTROL

This section gives some outlines of what we to believe to be possible areas of fruitful development. Up to now, many advanced control algorithms have been proposed and applied to looper-tension control problems. However, it is notable in section 3 that none of these schemes is entirely satisfactory.

- A SISO design was simple but there remains an interaction problem between angle and tension, consequently giving restricted performance.
- Optimal multivariable designs were effective methodologies to reduce interation effects but they were difficult to implement and tune.
- Robust controller designs guaranteed robust stability to disturbances and uncertainty. However, doing a controller design for worst case disturbances caused a deterioration of control performance overall.
- Co-ordinated control achieved good tension control performance but the ignored interations can imply significant limitations to controller gain.

A summary of the main design issues of looper-tension control that advanced control should tackle are: (1) minimization of disturbance and interaction effects; (2) robust stability guarantee; and (3) constraints satisfaction for quality requirements and operation stability. In order to satisfy all these specifications it will be very useful to include a gauge control model for controller design because major disturbances in looper-tension control come from the AGC actions.

There have been some multivarible design approaches which include a gauge model in the looper-tension control (Okada et al. (1998), Hearns and Grimble (2000b) and Hearns et al. (2004))

but none of them had a systematic co-ordination between mass flow and thickness. Hearns et al. (2004) emphasized the importance of the interaction between loop length and exit thickness, and tried a performance trade off between mass flow control and gauge control by changing the output weightings. In some cases the weights can be changed to ensure stable mill operation at the expense of exit gauge control. However, in this scheme it was difficult to implement a systematic weighting change according to process operating condition.

Therefore, one valuable research direction in the future will be co-ordinated control by an MPC algorithm which integrates gauge, looper and tension models across all the stands. Systematic co-ordinations between mass flow and strip quality can be implemented by constraint handling. Mass flow limits can be defined as hard constraints which should not be violated in any case whereas tension and thickness specifications can be defined as soft constraints. In the case where prediction gives large AGC actions and abnormal conditions which enduce severe mass flow unbalance and constraint violations, the MPC should compute controls to avoid this condition by allowing some slack in the control of thinkness. Therefore, the process should operate with best quality within permissible mass flow performance. The incorporation of a gauge model to the looper-tension control model also enables one to achieve better observation of the disturbances and therefore better control performance than with just looper-tension control. However, in order to apply this scheme to industry, a major obstacle to overcome is the implied computational burden associated with the prediction and constraint handling.

## 5. CONCLUSIONS

In order to improve control performance and stability for looper–tension control, various control algorithms have been developed. Conventional PI control schemes have been used most widely in industry regardless of the performance limitations, because they do not need tension meters. Where a tension measurement is available, many multivariable control algorithms have also been applied, but their main problems come from the complexity of the controllers with the consequent in difficulty of tuning. This paper contributes by giving a survey of all these various control algorithms, drawing together the strengths and weaknesses and hence demonstrating some areas of potential future development. In particular it is noted that none of the schemes as yet proposed in the literature combine simplicity and effectiveness to a degree that is desirable.

We propose that one avenue that has been substantially under explored is model predictive control. This has the facility to handle the large interactions (both inter- and intra–stand) within hot rolling mills and at the same time to take proper account of the hard constraints within the system. Moreover, it is possible in principle to take systematic account of both the known and unknown disturbances, the rejection of which consitutes a main control challenge. The main immediate goals in our future work are designing a suitable model and formulating a robust MPC algorithm which can be implemented at fast enough sample rates in the real industrial environment.

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