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An MPC Strategy for Hot Rolling Mills and Applications to Strip Threading Control Problems

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Abstract: Strip threadability is an ability to keep a strip flowing smoothly between inter-stands and run-out tables without severe longitudinal and lateral movements. The occurrence of a longitudinal movement is mainly related to looper–tension control performance, while a lateral movement is affected by steering control actions. Unstable threading may induce folding and pinching of a strip, thus resulting in damage to the strips and rolls and, in the worst case, an emergency shutdown. This paper investigates the potential of an MPC algorithm for the strip threading control problem and evaluates its efficacy through looper–tension and strip steering control case studies.

1. INTRODUCTION

Strong worldwide competition and the environmental restrictions associated with steel manufacturing demand the production of a cost–effective and a high–grade product. This motivates the increased interest in applying advanced control strategies (Bulut et al. [2000], Cannon et al. [2003]) such as MPC (Model Predictive Control) to the steel industry. MPC is one of the most popular advanced control techniques in industry, and particulary relevant here, mainly because of its ability for systematic on–line constraint handling (Rossiter [2003]).

In the meantime the HRM (Hot Rolling Mills) process, as a final or an interim producer of steel products, plays an important role in quality of the products. Major issues in the HRM process are based around the specification of quality and include such items as the thickness, width, profile and flatness of the products, as well as smooth threading of a strip. Strip threadability is an ability to keep a strip flowing smoothly between inter-stands and run-out tables without severe longitudinal and lateral movements. The occurrence of a longitudinal movement is mainly related to the performance of the looper–tension control, while a lateral movemnet is affected by steering control actions. Unstable threading may induce folding and pinching of a strip resulting in damage to the strips and rolls and even an emergency shutdown in the worst case.

Up to now, many control algorithms have been applied to these control loops in an attempt to achieve sufficient quality of threadability, but their design specifications were typically focused on a guarantee of stability and control performance under disturbances. The use of MPC on the other hand enables the additional flexibility to include constraint handling performance into the controller design specifications. Therefore, the purpose of this paper is to investigate the potential of an MPC algorithm for HRM control problems and evaluate its efficacy through two case studies: i) looper–tension control and ii) strip steering control.

2. MPC FORMULATION FOR DISTURBANCES

Disturbances are the major sources of the perturbations in strip threading. Hence in this section an MPC algorithm focussing on effective handling of disturbances is introduced. For the controller formulation, the following linear time–invariant (LTI) discrete system is considered.

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + Ew_k \\ y_k &= Cx_k + Du_k \end{aligned} \tag{1}$$

where $k = 0, \cdots, \infty$. Let the input predictions within the MPC control law (Scokaert et al. [1998], Rossiter et al. [1998]) be:

$$\begin{aligned} u_k &= -Kx_k + c_k \quad & k = 0, \cdots, n_c - 1 \\ u_k &= \quad -Kx_k & k \geq n_c \end{aligned} \tag{2}$$

where K represents a stabilizing feedback gain without constraints and c_k are d.o.f. available within the predictions to enable constraint handling. The performance index is defined by

$$J = \sum_{k=0}^{\infty} x_k^T Q x_k + u_k^T R u_k \tag{3}$$

Substituting (1, 2) into (3), the predicted performance J can be simplified to:

$$J = \sum_{j=0}^{i-1} c_j^T \hat{Q} c_j + p \; ; \quad p = x^T V x \tag{4}$$

where $\hat{Q} = B^T \Sigma B + R$, $\Sigma - \Phi^T \Sigma \Phi = Q + K^T RK$. Further simplification gives:

$$J = C^T W_D C \; ; \quad C = [c_0^T, \cdots, c_{n_c-1}^T]^T \tag{5}$$

where, $W_D = diag(\hat{Q}, \cdots, \hat{Q})$. Assume that the process (1) is subject to constraints:

$$\underline{u} \leq u_k \leq \overline{u} \ ; \ \underline{x} \leq x_k \leq \overline{x}; \ \underline{y} \leq y_k \leq \overline{y}, \quad k = 1, \cdots, \infty \tag{6}$$

The disturbances affecting the strip threading, such as variations of entry thickness, wedge, an initial off-center etc., will be modelled as random disturabnces. Moreover, as most of the output constraints in the processes do not need to be respected strictly, it is convenient (and realistic) to replace the deterministic constraints (6) by the following probabilistic constraints.

$$\begin{array}{ll} Pr\{y_k \leq y_{max}\} \geq \alpha_y & k = 0, \cdots, \infty, \\ Pr\{y_k \geq y_{min}\} \geq \alpha_y & k = 0, \cdots, \infty, \end{array} \tag{7}$$

where $Pr\{y_{inequality}\}$ is the probability that output y satisfies the constraint and α_y is the specified probability or required confidence level. The performance index is also defined using expected values:

$$J = \sum_{k=0}^{\infty} (r_k - \bar{y}_k)^T Q (r_k - \bar{y}_k) + \bar{u}_k^T R \bar{u}_k \tag{8}$$

where $\bar{y}_k$, $\bar{u}_k$ represents the expected values of y_k and u_k. Simple algebra (omitted for brevity) is sufficient to manipulate this cost into the equivalent form of (5).

The use of expected performance in the cost and constraints (7) results in less conservative control in the optimisation compared with the use of worst case performance measures. Moreover, chance constraints (7) can be transformed to the following linear constraints (thus simplifying the optimisation) in case where the probability density of y is known (Schwarm and Nikoaou [1999]).

$$\begin{array}{rcl} \bar{y}_k & \leq & y_{max} - K_{\alpha_y} \sigma_{\hat{y},k} \\ -\bar{y}_k & \leq & -y_{min} - K_{\alpha_y} \sigma_{\hat{y},k} \end{array} \tag{9}$$

where K_{α_y} is the value of the inverse cumulative distribution function of the standard normal distribution evaluated at α_y, and $\sigma_{\hat{y},k}$ represents standard deviation of the process output.

Algorithm 1. A chance–constrained robust MPC: At each sampling instant, perform the following QP optimisation:

$$\min_C J = C^T W_D C \quad s.t. \quad M_C x + N_C C \leq d_C \tag{10}$$

where M_C, N_C, d_C are suitable matrices representing (9). The use of CCRPC ensures a constraint satisfaction up to a given confidence level for random disturbances and with guaranteed stability.

3. CASE STUDIES FOR STRIP THREADING CONTROL

This section evaluates the efficacy of the CCRPC algorithm discussed in the previous section through two case studies associated with strip threading in hot rolling mills.

3.1 Looper–tension control

The control target in looper–tension control is to maintain looper angle and strip tension simultaneously at their desired values. However, the most difficult challenges in the controller design arise from the interaction, between strip tension and looper angle and the uncertainty coming from disturbances. The use of a robsut MPC algorithm gives looper–tension control improved constraint handling performance, which contributes to the improvement of product quality and stabilisation of the process in hot rolling mills.

3.2 Strip steering control

Strip steering is a lateral movement of a strip on the table rollers arising from asymmetric rolling of a strip. The steering changes rapidly due to the double integration of strip angular velocity and so it is difficult to control. Major sources of asymmetric strip rolling are an initial off-center, differences of strip temperature and a roll gap in the width direction, wedge of a strip, etc. The control target is to keep a strip going straight despite the disturbances by controlling the roll gap difference in the width direction. Conventional controllers P or PD have been applied (Steeper and Park [1998]), but the range of controller gains to ensure stability was narrow.

Here, an acceptable range of lateral movement and control limits to ensure a smooth threading are defined as soft constraints and included in a MPC formulation. The MPC control law, which satisfies the constraints and optimises the performance over the prediction horizon, gives better control performance than conventional controllers.

4. CONCLUSION

This paper investigated the potential of a MPC algorithm for hot rolling mills. It is shown that MPC can improve control performance substantially with a small sacrifice of constraint handling performance. Moreover, the paper evaluated efficacy by applying the MPC algorithm to a strip threading control problem.

REFERENCES

P.O.M. Scokaert and J.B. Rawlings, Constrained linear quadratic regulation, EEE Trans on AC, 43(8) (1998) 1163–1168.

J.A. Rossiter, B. Kouvaritakis, M.J. Rice, A numerically robust state-space approach to stable predictive control strategies, Automatica, 34(1998) 65-73.

J. A. Rossiter (2003), Model–based predictive control: A practical approach, CRC Press, 2003.

B. Bulut and M. R. Katebi and M. J. Grimble, Predictive control of hot rolling processes, in: Proceedings of the American Control Conference (2000), Chicago, Illinois, USA.

M. Cannon and B. Kouvaritakis and M. Grimble and B. Bulut, Nonlinear predictive control of hot strip rolling mill, International Journal of Robust and Nonlinear Control, 13(2003) 365–380.

A. T. Schwarm and M. Nikolaou, Chance-Constrained Model Predictive Control, AIChE Journal, 45(8) (1999) 1743–1752.

M. J. Steeper and D. G. Park, Development of steering control system for reversing hot mills, Iron and Steel Engineer, November (1998) 21–24.