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AN LPV APPROACH FOR ACTIVE ROLL ECCENTRICITY COMPENSATION

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Abstract: In this paper a new identification scheme to perform roll eccentricity compensation for rolling mills is proposed. The method presents the advantage that it can be easily tuned in function of the main frequency in the periodic disturbance that, in turn, is dependent on the rolling speed. *Copyright © 2002 IFAC*

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1. INTRODUCTION

In many practical situations there is the problem of manufacturing cylindrical objects with cross-sections which approach the shape of a circle with a desired tolerance. This necessity is present also for the production of wide sheet or foil materials such as paper, plastic film, steel and aluminium that are passed through pre-loaded cylindrical rolls (see Edwards et al. 1987) .

In Fig. 1 a typical rolling mill for the production of steel or aluminium is outlined. One of the most important problems is represented by the necessity of guaranteeing high precision for the exit thickness that can be compromised by the eccentricity of the backup rolls.

The phenomenon of roll eccentricity is caused by several reasons: inexact roll grinding, nonuniform thermal expansion of the rolls, etc. The problem is considered till now open and is the subject of intensive research (see e.g. Kugi et al. 2000b and references quoted therein).

The most promising approaches for roll eccentricity compensation take advantage of the fact that the disturbance generated is a periodic signal with a frequency that is proportional to the measured angular speed of the rolls. It is worth noticing that the main frequency of this periodic disturbance signal is not completely *a-priori* known due to variations in the rolling speed. On the other hand, this parameter is on-line measured. For this reason the application of Linear Parameter Varying (LPV) (see Apkarian and Adams, 1998) control techniques is here proposed.

In order to compensate roll eccentricity several methods have already been proposed in the literature (see Kugi et al. 2000b, Kugi et al. 2000a and Katebi,

1999): Kalman filtering, Fast Fourier Transformation (FFT) based methods, etc.
It is necessary to point out that the control problem is getting more complicated for the following main reasons:

- The eccentricity compensation must coexist with the conventional Automatic Gauge Control (AGC) system and in particular with the gaugemeter functionality that when is implemented without eccentricity compensation can be counterproductive.
- Upper and lower backup rolls have in general different diameters and for this reason the eccentricity signal may contain two harmonics whose frequencies are very close.
- The rolling speed is not a constant and, consequently, the main frequency of the eccentricity disturbance is not constant but time varying.

In view of these difficulties, methods based on *Kalman* filter suffer of a main drawback represented by the fact that *it is difficult to tune the compensator in function of the time-varying fundamental frequency of the eccentricity disturbance*. On the other hand *FFT methods* seem more effective *but they need a large amount of data to become effective*: this fact can turn out in a slow compensation.

The LPV compensation technique proposed in this paper consists of a new filter for compensation that with respect to the classical Kalman filter offers the following main advantages:

- The LPV filter can be tuned in function of the measured frequency of the periodic eccentricity disturbance. This advantage is achieved by resorting to convex optimisation techniques (see Boyd *et al.* 1994) applied to a polytopic type uncertain system.
- An H_∞ filtering criterion, which is the most suitable in presence of disturbances that cannot be considered of Gaussian type and whose stochastic features are not available, is adopted.
- Last but not least, the filtering method can be easily robustified towards model norm bounded uncertainties.

It is worthwhile pointing out that it is also possible to take into account the presence of many harmonics in the periodic disturbance signal. More precisely, it is possible to consider the presence of two main harmonics due to different radii for the upper and lower backup rolls.
The paper is organised as follows. In Section 2 the main issues concerning eccentricity compensation are described and in Section 3 the estimation technique based on Linear Parameter Varying (LPV) concepts, is introduced. Finally, in Section 4 some numerical examples based on a MATLAB/SIMULINK simulator are proposed.

This section is concluded with some notation that is used through the paper. As usual M>0 (<0) means that the symmetric matrix M is positive (negative) definite. The L_2 norm of a vector valued function $f(t)$ is

$$\|f\|_{L_2} := \left\{ \int_{t=0}^{\infty} f(t)^T f(t) dt \right\}^{1/2} .$$

The symbol * will be used in some matrix expressions in order to induce a symmetric structure. For example, in case L and R are symmetric matrices, then

$$\begin{bmatrix} L+M+* & * \\ N & R \end{bmatrix} := \begin{bmatrix} L+M+M^T & N^T \\ N & R \end{bmatrix}.$$

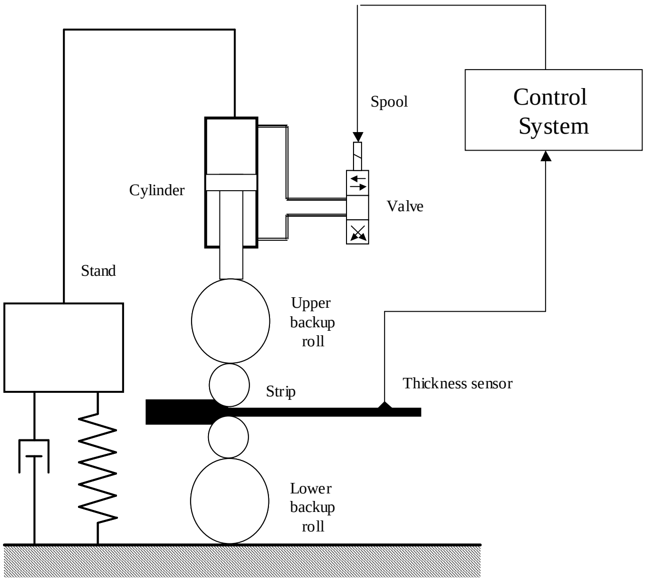

Fig. 1. The process for the production of a steel strip with a given thickness by using rolling mills.

2. PROBLEM SETTING

As proposed in many previous works about roll eccentricity compensation it is possible to state that the exit thickness deviation Δh_{tot} around a given operating point is

$$\Delta h_{tot} := \frac{\Delta F_{roll}}{M_m} + e + \Delta s \qquad (1)$$

where ΔF_{roll} is the roll force deviation, $\frac{\Delta F_{roll}}{M_m}$ represents the elastic deformation of the stand with respect to the elastic constant M_m (the so-called Mill Modulus), e is the periodic eccentricity signal to be compensated and Δs is the gap adjustment that is produced by the control system and in particular by the gaugemeter functionality. The latter aims at compensating the elastic deformation by estimating the

Mill Modulus coefficient M_m. In other words it is possible to compensate the elastic deformation by imposing

$$\Delta s = -\frac{\Delta \hat{F}_{roll}}{\hat{M}_m} \qquad (2)$$

where $\Delta \hat{F}_{roll}$ and $\hat{M}_m$ are the estimates of the roll force deviation and of the Mill Modulus respectively. In many applications, when the effect of the roll eccentricity *e* is excessive, this gaugemeter functionality can turn out counterproductive. This is due to the fact that when the periodic eccentricity signal *e* has excessive amplitude then the estimate of the roll force deviation ΔF_{roll} can be compromised and the gaugemeter functionality as well.

It is possible to recover this functionality by a feedforward compensation of the eccentricity effect *e*. This can be done by generating a compensation signal out of the measured roll force deviation ΔF_{roll} or out of the measured thickness deviation Δh_{tot}.

In both cases it is necessary to estimate a periodic signal of known frequency from a measured signal $y(t)$. More precisely, this measured signal (the measured roll force deviation $\Delta \hat{F}_{roll}$ or the measured thickness deviation $\Delta \hat{h}_{tot}$) is composed of two signals as follows:

$$y(t) = d(t) + p\, z(t) \qquad (3)$$

where $d(t)$ is the periodic signal of known frequency (having zero average value), $z(t)$ is the measured signal deprived of the periodic component and the parameter *p* is a coefficient that can be used as a tuning knob.

As it is well known the periodic signal $d(t)$ can be expanded in Fourier series as:

$$d(t) = \sum_k d_k(t)$$

where if T=1/(2πΩ) is the period of $d(t)$ then $d_k(t)$ is the spectral line corresponding to the frequency $k\Omega$. In the following we assume that only the fist *m* harmonics are significant. An appropriate state space model for the generic harmonic $d_k(t)$ is given by the second order model

$$\begin{cases} \dot{\xi}_k(t) = W_k(\Omega)\xi_k(t) \\ d_k(t) = h\xi_k(t) \end{cases} \qquad (4)$$

where

$$W_k(\Omega) = \begin{bmatrix} 0 & -k\Omega \\ k\Omega & 0 \end{bmatrix},$$
$$h = [1 \quad 0]. \qquad (5)$$

Consequently, by piling up all state vectors of the considered harmonics $d_1(t)$, $d_2(t)$, …, $d_m(t)$ one obtains the overall model for the periodic disturbance $d(t)$ (see Bittanti and Cuzzola, 2002b) as follows:

$$\begin{cases} \dot{\xi}(t) = W(\Omega)\xi(t) \\ d(t) = H\xi(t) \end{cases} \qquad (6)$$

with

$$W(\Omega) = diag_{i=1}^{k}(W_k(\Omega)),$$
$$H = [h \quad h \quad \dots \quad h]. \qquad (7)$$

The problem now is to estimate the signal $d(t) = H\xi(t)$ from the measurement of the signal $y(t)$ (see eq. (3)) and this is a typical filtering problem. It is important to note that if the basic frequency Ω is constant and known, the problem corresponds to filtering a linear and time invariant system and the task of estimating $d(t)$ can be attained by means of classical filtering techniques as Kalman filtering. Unfortunately, Ω cannot be considered a constant since the rolling speed in general is not a constant. Nevertheless it is possible to assume that

$$\Omega \in [\Omega_m \quad \Omega_M] \qquad (8)$$

where Ω_m and Ω_M are the minimal and maximal admissible frequencies for the basic harmonic. It is straightforward to prove that if the scalar $\lambda \in [0 \quad 1]$ is such that $\Omega = \lambda\,\Omega_m + (1-\lambda)\,\Omega_M$ then

$$W(\Omega) = \lambda\, \mathrm{W}(\Omega_m) + (1-\lambda)\, \mathrm{W}(\Omega_M). \qquad (9)$$

Consequently, if Ω is not a constant, the problem turns out the problem of filtering a uncertain polytopic system (see Boyd *et al.* 1994) and the vertices of the uncertainty polytope are represented by $\mathrm{W}(\Omega_m)$ and $\mathrm{W}(\Omega_M)$. In other words, the system (6) is a Linear Parameter Varying (LPV) system that is varying with the parameter λ.

Remark 1*: Estimation of the frequency of the basic harmonic.*

In general the quantity Ω could be considered a known and online measured parameter. Nevertheless it could be subject to uncertainty. In order to improve the knowledge about this frequency it is worth resorting to classical techniques like that presented in Bittanti and Savaresi, 2000 where an effective procedure to estimate the frequency of periodic signals is presented.

In this way the LPV technique for Roll Eccentricity Compensation procedure can be refined by a two-step rationale (see Fig. 2): the first step is the estimation of the parameter Ω from the measurement of the signal $y(t)$ (see eq. (3)). This task can be easily performed by means of the technique described in Bittanti and Savaresi, 2000. The second step is the estimation of the periodic signal $d(t)$ achieved by an LPV filter that is tuned according to the estimate of Ω and that will be the subject of the following part of this paper. ❑

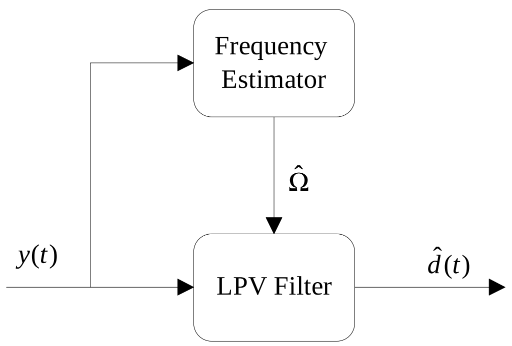

Fig. 2. The Roll Eccentricity Compensation rationale.

3. THE LPV H∞ FILTERING APPROACH

In this section an LPV approach to estimate the quantity $d(t)$ from the measurement of a whatever signal $y(t)$ (see eqs. (3) and (6)) is proposed. In a nutshell, we want to synthesise a suitable filter that can be tuned in function of the online measured parameter Ω representing the basic frequency of the periodic signal. The candidate filter has the following structure:

$$\begin{cases} \dot{\xi}_F(t) = A_F(\Omega)\xi_F(t) + B_F(\Omega)y(t) \\ \hat{d}(t) = C_F(\Omega)\xi_F(t) + D_F(\Omega)y(t) \end{cases} \quad (10)$$

where $\xi_F(t) \in \Re^{2m}$ is the state of the estimator and $\hat{d}(t) \in \Re$ is the estimate of $d(t)$.

From the beginning it has been postulated the so-called unbiasedness of the estimator by imposing $A_F(\Omega) = W(\Omega) - B_F(\Omega)H$, $C_F(\Omega) = H - D_F(\Omega)H$ (the interested reader is referred to Bittanti and Cuzzola, 2001a and Cuzzola and Ferrante, 2001 for some detail about unbiased filtering).

Moreover, by letting $e(t) = d(t) - \hat{d}(t)$ the estimation error, the filtering problem is tackled in an H_∞ framework by imposing a bound γ on the L_2 gain between the input signal $z(t)$ (see eq. (3)) and the estimation error $e(t)$

$$\sup_{w \in L_2 - \{0\}} \frac{\| e(t) \|_{L_2}}{\| z(t) \|_{L_2}} < \gamma . \quad (11)$$

Such filter can be easily derived by means of Linear Matrix Inequality (LMI) optimisation through the procedure represented by the following theorem whose proof is left to the reader for the sake of brevity:

Theorem 1: Synthesis of the LPV H_∞ filter.
Consider the LPV system (3), (6), (9). There exists an unbiased filter of the type (10) guaranteeing the H_∞ performance (11) if the following LMI constraints have a solution with respect to the unknowns $\{P_m, P_M, Y_m, Y_M, D_{Fm}, D_{FM}, V\}$ of suitable dimensions:

$$P_m = P_m^T, \; P_M = P_M^T$$

$$\begin{bmatrix} -V + * & V^T W(\Omega_m) - Y_m H + P_m & -Y_m p & V^T & 0 \\ * & -P_m & 0 & 0 & (H - D_{Fm} H)^T \\ * & * & -\gamma^2 I & 0 & -p D_{Fm}^T \\ * & * & * & -P_m & 0 \\ * & * & * & * & -I \end{bmatrix} < 0 \quad (12.1)$$

$$\begin{bmatrix} -V + * & V^T W(\Omega_M) - Y_M H + P_M & -Y_M p & V^T & 0 \\ * & -P_M & 0 & 0 & (H - D_{FM} H)^T \\ * & * & -\gamma^2 I & 0 & -p D_{FM}^T \\ * & * & * & -P_M & 0 \\ * & * & * & * & -I \end{bmatrix} < 0 \quad (12.2)$$

The filter parameters $\{ A_F(\Omega), B_F(\Omega), C_F(\Omega), D_F(\Omega) \}$, can be computed directly from the solution of this LMI optimisation problem by following this three step procedure:

1) Compute the matrices B_{Fm} and B_{FM} as follows:

$$B_{Fm} := V^{-T} Y_m , \qquad B_{FM} := V^{-T} Y_M .$$

2) Find the scalar $\lambda \in [0 \quad 1]$ such that $\Omega = \lambda \, \Omega_m + (1 - \lambda)\, \Omega_M$ then

$$B_F(\Omega) = \lambda \, B_{Fm} + (1 - \lambda)\, B_{FM} ,$$
$$D_F(\Omega) = \lambda \, D_{Fm} + (1 - \lambda)\, D_{FM} . \quad (13)$$

3) The remaining filter parameters $A_F(\Omega)$, $C_F(\Omega)$ are given by the unbiasedness conditions:

$$A_F(\Omega) = W(\Omega) - B_F(\Omega)H ,$$
$$C_F(\Omega) = H - D_F(\Omega)H . \quad (14)$$

Proof
The proof, which is here omitted for the sake of brevity, is a consequence of the results reported in Bittanti and Cuzzola, 2001a and Apkarian et al. 2000.

❑

Remark 2: Conservativeness of the LMI synthesis approach.
The synthesis approach of Theorem 1 is based on the fact that the polytopic uncertain system (6) is defined

as a convex combination of two extreme conditions represented by $W(\Omega_m)$ and $W(\Omega_M)$ (see Section 2). In general control and filtering problems for these systems are based on the use of a single quadratic Lyapunov function (the so-called quadratical stabilizability, see e.g. Boyd *et al.* 1994). In Theorem 1, it has been proposed extending the results of Apkarian et al. 2000 to the particular estimation problem described before in order to achieve less conservative results. Indeed, the filtering problem is faced here by using two Lyapunov matrices (the symmetric and positive definite unknowns P_m and P_M of the LMI synthesis problem of eqs. (12)) each of which is corresponding to a different vertex of the uncertainty polytope. Anyway, it is important to stress that in general this new approach does not guarantee the optimality. ❑

4. VALIDATION EXPERIMENT

In this section some numerical examples are proposed. To this purpose we exploit a MATLAB/SIMULINK simulator containing the stand model, the hydraulic system (pipes and valve), the strip model for the computation of the rolling force, a sensor delay for the measurement of the exit thickness and the AGC regulator. The following periodic disturbance to be compensated is injected in the *exit thickness signal* (before of the sensor model):

$$d(t) = 100e-6sin(2\pi\,\Omega\,t) + 50e-6\cos(4\pi\,\Omega\,t)\,. \quad (15)$$

This periodic disturbance can be generated by a dynamic system of the type (6) with $\Omega = 1$ and $m = 2$. Furthermore a variation of Ω is considered as follows:

$$\Omega(t) = \begin{cases} 1, & \text{if } t < 10 \\ 1 + (0.1/3)(t-10), & \text{if } 10 \le t \le 13 \\ 1.1, & \text{if } t \ge 13. \end{cases} \quad (16)$$

In this case the LPV filter has been tuned by imposing $\Omega_m = 1$ and $\Omega_M = 1.1$. In Fig. 3 the rolling force signal F_{roll} due to the presence of the periodic disturbance $d(t)$ on the exit thickness, is shown. In order to make more difficult the estimation problem a further noise is added in the measured rolling force:

$$F_{meas} = F_{roll} + r(t) \quad (17)$$

where F_{meas} is the measured rolling force (see Fig. 4) and the noise $r(t)$ is

$$r(t) = 1e5w(t) + 5e5sin(20.5t + 3)\,,$$
$$w(t) \sim WN(0,1)\,. \quad (18)$$

In Fig. 5 the periodic disturbance F_e acting on the rolling force F_{roll} and its estimate $\hat{F}_e$ are depicted. As one can note from the latter figure, the compensation filter has a good performance until the time instant 10 sec. During the transient period (from 10 sec. to 13 sec.) in which the frequency of the basic harmonic $\Omega(t)$ is linearly varying (see eq. (16)), the compensation performance is slightly deteriorated but after this transient period an optimal performance is promptly recovered.

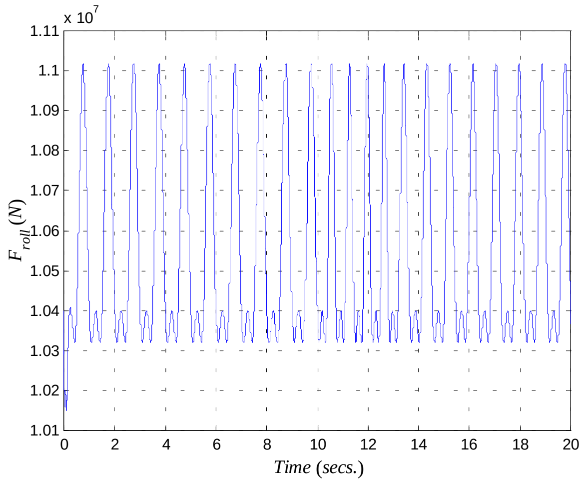

Fig. 3. The rolling force F_{roll}.

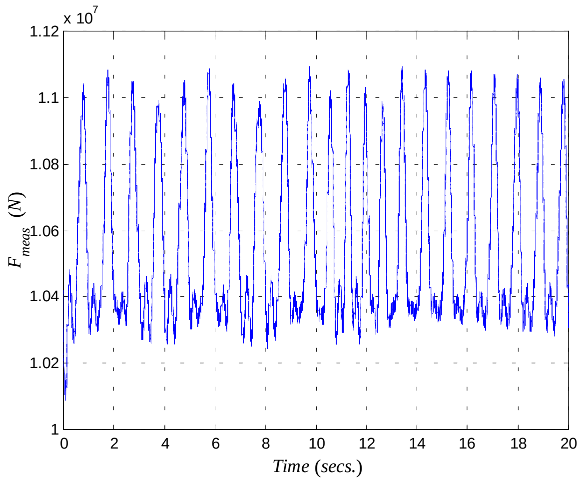

Fig. 4. The measured rolling force F_{meas}.

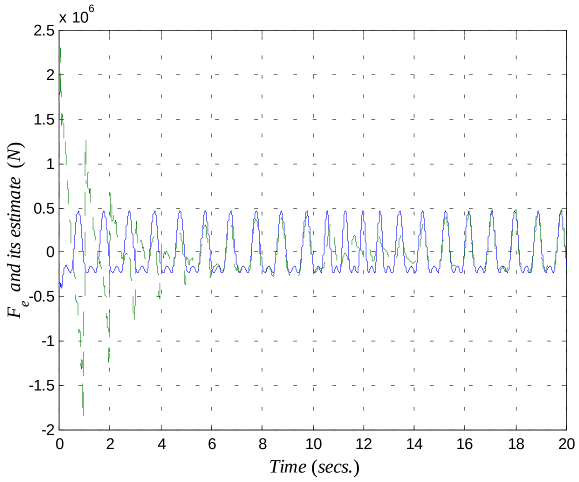

Fig. 5. The periodic disturbance F_e acting on the rolling force (solid line) and its estimate (dashed line).

5. CONCLUSIONS

In this work a new technique based on LPV concepts has been proposed to compensate roll eccentricity in rolling mills. The main assumption is that the rolling speed (and, equivalently, the angular speed of the backup rolls) is measured and that the compensation filter is online tuned according to this parameter.

This method can be improved in many directions: one of the most interesting is the fact that it is possible to remove the assumption that the frequency of the periodic eccentricity disturbance is an on-line measured parameter. Indeed, the estimation technique can be subdivided in a two step rationale: the first step is the estimation of the frequency of the main harmonic whereas the second step is the LPV filter described in the present paper and tuned according to the estimated frequency.

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