COMPENSATION OF IRREGULAR BACK-UP ROLL ECCENTRICITIES IN 4-HIGH AND 6-HIGH APPLICATIONS [1]

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Abstract

The compensation of back-up roll eccentricity is an established, mature and well understood concept that has seen many implementations with varying degrees of performance and success. A typical assumption in the compensator's internal model's structure and dynamics is that the offending and disruptive eccentricity signals are based on combinations of periodic roll ovality and rotation axis offset. In real-world cases, the disruptive eccentricities may have far more complex behavior stemming from improper roll grinding practices and / or poor metallurgical quality rolls having irregular / inconsistent patterned variations in surface hardness. These additional components tend to exceed the capabilities of contemporary eccentricity methods, leading to unacceptable exit gauge control and potentially unstable compensation reactions. This paper will examine and illustrate efforts to improve existing eccentricity compensation practices by considering disturbance estimation and feedforward cancellation coupled with adaptive parameter estimation and self-tuning regulation. Periodic classical and higher-order eccentric disturbances are estimated as a function of roll rotation from spatial decomposition of exit gauge temporal signals. Correlating these decomposed components and relating them to the tracked periodic rotation of the rolls within the stack, allows these un-modeled (pseudo-random periodic) components to be directly mapped to the surfaces of the individual rolls. These mapping functions can be applied to directly compensate for the overall roll stack irregularities by feedforward disturbance cancellation. Controller adaptation is provided by explicit descriptions within the internal models and through parameter identification coupled with self-tuning regulation to accommodate mill / material related variants.

Key words: Eccentricity disturbance estimation

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1 INTRODUCTION

Fundamental roll eccentricity distortions in diametral cylindricity (ovality) and adherence to the rotational axis (offset rotation) are, to some degree, inevitable. These eccentricities stem from a variety of sources (primarily improper roll grinding or poorly maintained roll grinding and mill equipment) and manifest their presence by imprinting well defined cyclic patterns onto the rolled strip. In 4-High and 6-High vertical stack mill configurations, the back-up roll eccentricities tend to be the worst offenders, primarily because the magnitudes of their distortions are proportionally larger than the other rolls in the stack. Equipment capability and product tolerances determine whether these distortions are of sufficient amplitude to induce detrimental effects, if left unattended.

Classical notions of back-up roll eccentricity consider only the offset rotation and ovality components. Figure 1 provides graphical defining descriptions of these components and relationships to the back-up roll geometry and coordinate frames.

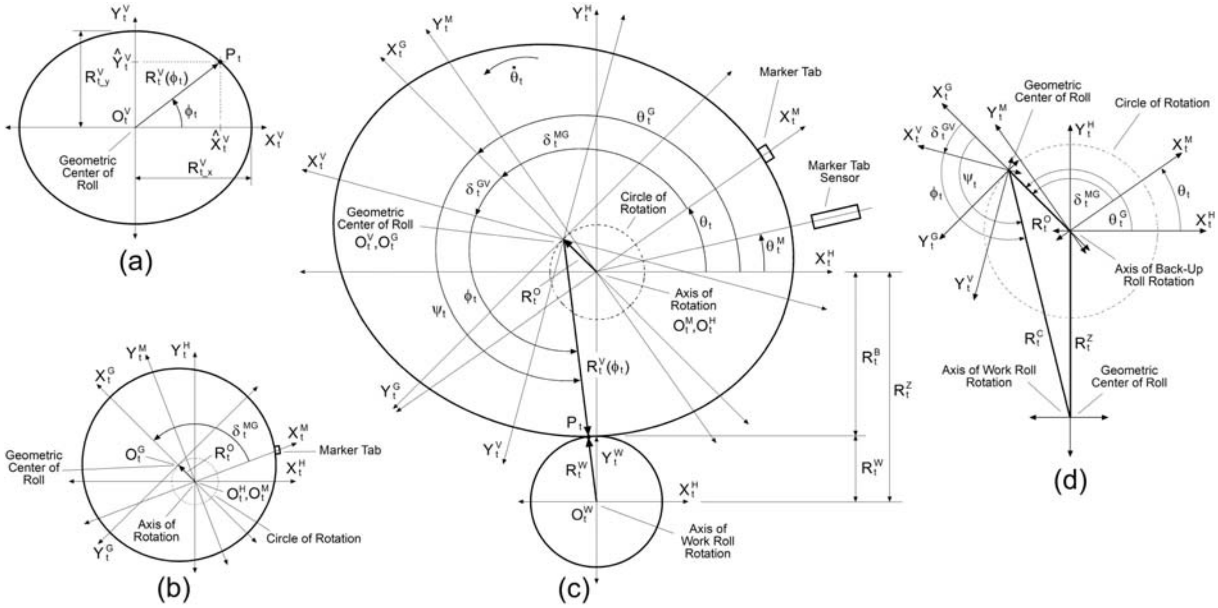
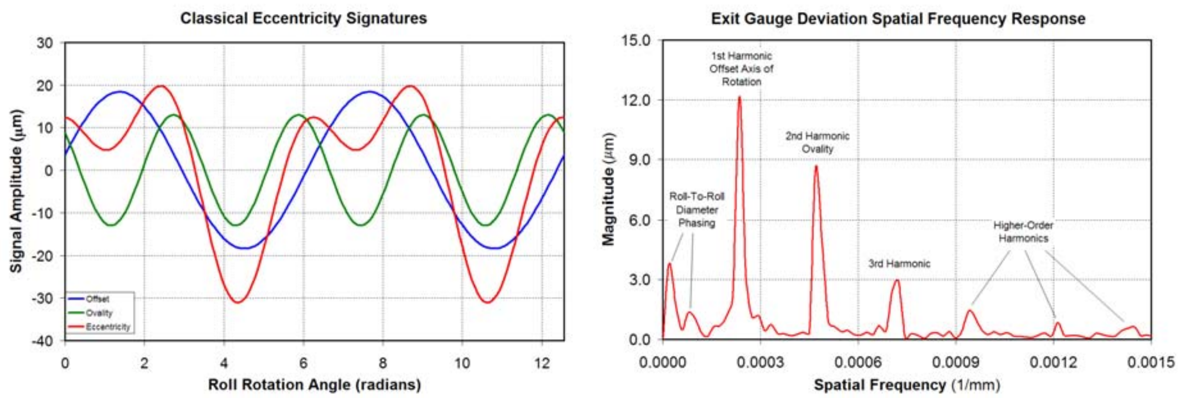


Figure 1. Graphical descriptions of the classical components of back-up roll eccentricity: a) Roll barrel ovality, b) Offset rotation due to the misalignment of the roll's geometric cylindrical axis and the axis of rotation, c) Composite definition of all associated coordinate frames, roll geometries and rotational axes, d) Detailed geometric relations that govern the behavior of eccentric imprinting.

Theoretically / ideally, these eccentricity components induce characteristic periodic patterns in the rolled strip:

- Offset Rotation – Sinusoidal pattern having a periodic evolution over a single rotation of the roll (1^{st} harmonic of roll rotation).
- Ovality – Sinusoidal pattern having two (2) periodic evolutions over a single rotation of the roll (2^{nd} harmonic of roll rotation).

There is no constraint in the phase or amplitude relationships between these components and therefore a broad range of possible eccentric patterns can be expected. Figure 2 illustrates the rotational characteristics of a single roll having offset and ovality eccentricities and the spatial frequency characteristics for an actual 4-High mill.



(a) (b)

Figure 2. Illustrations of the eccentricity rotational and spatial frequency characteristics: a) Classical eccentricity signal evolutions of the offset, ovality and composite eccentricities as a function of roll rotation angle, b) Spatial frequency characteristics of the exit gauge on an actual 4-High mill.

It is important to note that the spatial frequency characteristics indicate a more complicated eccentricity system at work in the actual mill (Figure 2b). The presence of sub-harmonic, 3rd and higher order harmonic terms indicate that the true roll eccentricities are more complex than the classical assumption provides.

Higher order harmonic components stem from uneven bearing journals, roll surface hardness variations, mechanical roll grinder deflections, etc. Sub-harmonic components have less obvious origins, like: crossing and shifting rolls due to loose mill frame and chock liners, sloppy roll force cylinders that wobble and tilt, low frequency resonances, etc. Many (if not all) of these can be excluded from concern by proper design and maintenance.

Unfortunately, throughout the world, there are a great many “underprivileged” mills and facilities that can not accomplish and maintain the necessary mechanical tolerances, either because of a lack of proper maintenance capacity or financial resources, or because of acquiring or inheriting poorly designed or manufactured equipment. As industry tolerances tighten and customer expectation heighten, these mills are loosing market shares important to their survival.

Advances in machine automation and control system techniques offer these mills some reprieve from their shortcomings by offering strategies to attenuate the detrimental effects. Roll eccentricity compensation techniques are well understood, mature subjects employing a wide range of methods.[1-10] Many limit themselves to consider only the classical offset and ovality terms, however some extend the coverage to the higher order terms.[6,7]

This paper investigates an alternative approach that employs disturbance estimation coupled with feedforward compensation[11-15] to reject the characterizable components of the offending roll stack distortions. An internal model of the disturbing distortions is directly embedded within the Luenberger estimator[16,17] to render state reconstruction of the periodic eccentricity components under consideration. These real-time estimates are applied to feedfoward cancellation techniques to directly counter the disturbing effects. This approach has ties to repetitive control[6] but approaches the problem from the perspective of disturbance estimation and compensation.[11-15]

The estimation process relies on the accuracy of its internal model of the eccentricity components. These components vary with every roll change and exhibit temporal and spatial phasing because of differing roll diameters and roll contact slip. It is therefore necessary to incorporate some degree of active adaptation to accommodate these variations in both set-up and on-line activities. Eccentricity signature characterization can be carried out during post roll change mill alignment, roll facing or mill modulus measurements. Parameter identification coupled with self-tuning regulation techniques are applied to actively determine key / sensitive model parameters and adjust the compensation laws to maintain control specifications.

2 CHARACTERIZING IRREGULAR ECCENTRICITIES

The classical offset rotation and ovality components do not completely characterize the true nature of roll eccentricities. The real-world example of Figure 2b clearly shows that higher order components are involved. Further sub-harmonic components are also evident, that can be attributed to phasing / beating associated with differential roll diameters, roll shifting and crossing, wobbling / tilting roll force cylinders, etc. Figure 3 shows a more realistic depiction of actual roll eccentricities and their harmonic decompositions as a function of roll rotation angle. Figure 3e shows the differences between the classical modeled response to that modeled with higher and lower order components.

The m_D, eccentric disturbances, represented by the vector, $\mathbf{d}(t)$, are modeled as a known, $n_D{}^{th}$ order, deterministic, wave-form structured, linear, time-invariant disturbance system [11,12,15,18], $\Sigma_D(\mathbf{A}_D, \mathbf{C}_D)$, given by:

$$\dot{\mathbf{z}}(t) = \mathbf{A}_D \mathbf{z}(t) \qquad \mathbf{z}(0) = \mathbf{z}_0 \tag{1a}$$

$$\mathbf{d}(t) = \mathbf{C}_D \mathbf{z}(t) \tag{1b}$$

With $\mathbf{z}_0$ having appropriate structure.[15,18,19] $\mathbf{A}_D$, $\mathbf{C}_D$ are structured and partitioned to model each sub- and super-harmonic eccentricity component, i, of each roll, j, as an independent 2[nd] order system having conjugate poles on the imaginary s-plane axis. This results in the diagonally dominant form having base sub-systems for each roll, with n_R being the number of rolls in the vertical stack.

$$\mathbf{A}_D = \begin{bmatrix} \mathbf{A}_D^1 & & & & \\ & \mathbf{A}_D^2 & & \varnothing & \\ & & \ddots & & \\ & & & \mathbf{A}_D^j & \\ & \varnothing & & \ddots & \\ & & & & \mathbf{A}_D^{n_R} \end{bmatrix} \tag{2a}$$

$$\mathbf{C}_D = \begin{bmatrix} \mathbf{C}_D^1 & \mathbf{C}_D^2 & \cdots & \mathbf{C}_D^j & \cdots & \mathbf{C}_D^{n_R} \end{bmatrix} \tag{2b}$$

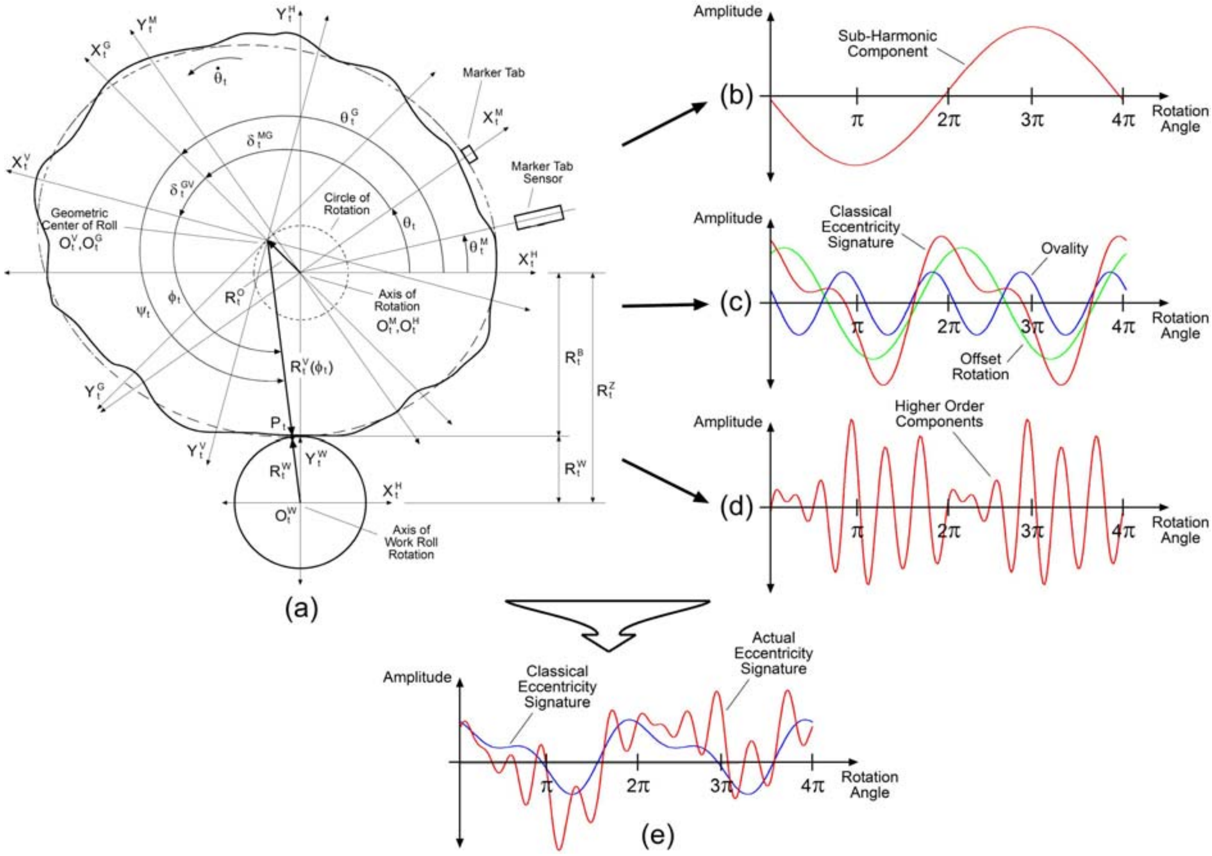


Figure 3. Illustration of the Sendzimir mill and its shape control actuators, along with the general form and structure of its characterization and modeling.

The roll based sub-systems are further decomposed into their n_h^j roll specific harmonic systems:

$$\mathbf{A}_D^j = \begin{bmatrix} \mathbf{A}_D^{1j} & & & & & \\ & \mathbf{A}_D^{2j} & & & \varnothing & \\ & & \ddots & & & \\ & & & \mathbf{A}_D^{ij} & & \\ & \varnothing & & & \ddots & \\ & & & & & \mathbf{A}_D^{n_h^j j} \end{bmatrix} \tag{3a}$$

$$\mathbf{C}_D^j = \begin{bmatrix} \mathbf{C}_D^{1j} & \mathbf{C}_D^{2j} & \cdots & \mathbf{C}_D^{ij} & \cdots & \mathbf{C}_D^{n_h^j j} \end{bmatrix} \tag{3b}$$

with the individual harmonic systems given by:

$$\mathbf{A}_D^{ij} = \begin{bmatrix} 0 & 1 \\ a_D^{ij} & 0 \end{bmatrix} \tag{4a}$$

$$\mathbf{C}_D^{ij} = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{4b}$$

where

$$a_D^{ij} = -\left(k_{ij} \frac{3}{25} \frac{S_S}{D_j} \right)^2 \tag{5}$$

where S_S is the strip speed (mpm), D_j is the j^{th} roll diameter (mm), and k_{ij} being of an ordered set of n_h^j elements that define the harmonic order of $\mathbf{A}_D^{ij}$:

$$k_{ij} = \left\{ \frac{1}{h_n^{ij}}, \ldots, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1, 2, \ldots, h_x^{ij} \right\} \quad (6)$$

with the harmonic range defined by the integers h_n^{ij} and h_n^{ij}:

h_n^{ij} - The reciprocal of the lowest sub-harmonic considered for roll j.

h_n^{ij} - The highest harmonic considered for roll, j.

and

$$n_h^j = h_x^j + \left(h_n^j - 1\right) \quad (7)$$

Therefore, the disturbance system model, $\Sigma_D\left(\mathbf{A}_D, \mathbf{C}_D\right)$, provide a highly flexible framework to account for an arbitrarily large, unique harmonic envelope for each roll. It is also possible to provide some degree of model reduction, when, during commissioning, certain roll harmonics are found to be of little or no consequence. In this case, certain harmonic components within the set , k_{ij}, can be excluded, causing Eq(7) to be invalid and n_h^j being the number of elements in k_{ij}.

Model adaptation is provided by the incorporation of roll diameter and strip speed within the elements of $\mathbf{A}_D$. Further, the organization and structure of $\mathbf{A}_D$ is highly diagonally dominant and sparse, allowing the computational overhead to be greatly reduced by sparse matrix methods.[20]

3.0 – Controller Development and Simulation Model

A simplified application of disturbance estimation and compensation to this eccentricity problem is based on the mill system is modeled as a known, n^{th} order, deterministic, linear, time-invariant system, $\Sigma\left(\mathbf{A}, \mathbf{B}, \mathbf{B}_D, \mathbf{C}\right)$, given by:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,x_P(t) + \mathbf{B}_D\,\mathbf{d}(t) \quad (8a)$$

$$\Delta G_X(t) = \mathbf{C}\,\mathbf{x}(t) \quad (8b)$$

where $x_P(t)$ is the roll force cylinder position and $\Delta G_X(t)$ is the exit gauge deviation. Under certain conditions, complete disturbance decoupling with internal stability[18,21-25] can be achieved with ideal state feedback, $\mathbf{K}_X$, and extended with disturbance state feedforward cancellation, $\mathbf{K}_Z$, with the ideal control law of:

$$x_P(t) = -\mathbf{K}_X\,\mathbf{x}(t) - \mathbf{K}_Z\,\mathbf{z}(t) \quad (9)$$

This results in the ideal system arrangement shown in Figure 4.

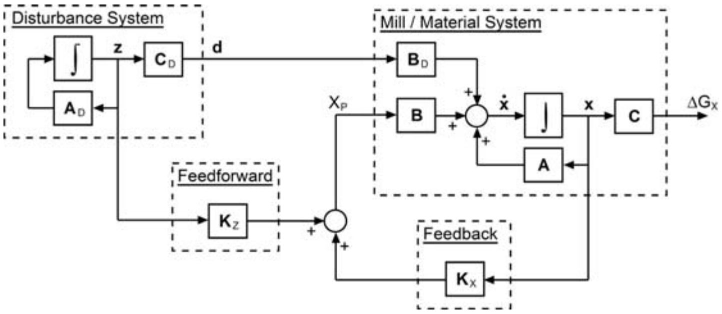


Figure 4. Block diagram of an ideal state feedback, disturbance state feedforward cancellation controller.

Unfortunately, the ideal controller configuration of Eq(9) and Figure 4 is non-realizable due to the inaccessibility of the system state, $\mathbf{x}(t)$ and the disturbance state, $\mathbf{z}(t)$. To overcome this difficulty, a composite dynamic observer[11-15,18] can be employed to reconstruct the mill / material state and disturbance state vectors (in real-time) from measures of the roll force cylinder position, $x_P(t)$, and exit gauge deviation, $\Delta G_X(t)$. The observer employs internal model replicas of the mill / material and disturbance systems to form the state vector estimates. Errors in the measured mill output, $\Delta G_X(t)$ and the estimated plant output, $\Delta \hat{G}_X(t)$, are used to adjust the estimation process (via $\mathbf{L}_X$ and $\mathbf{L}_Z$) and assure the specified asymptotically stable convergent behavior. The composite state / disturbance estimator is shown in Figure 5a and is given by:

$$\begin{bmatrix} \dot{\hat{\mathbf{x}}} \\ \dot{\hat{\mathbf{z}}} \end{bmatrix} = \begin{bmatrix} (\mathbf{A}-\mathbf{L}_X\mathbf{C}) & \mathbf{B}_D\mathbf{C}_D \\ -\mathbf{L}_Z\mathbf{C} & \mathbf{A}_D \end{bmatrix} \begin{bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{z}} \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \varnothing \end{bmatrix} x_P + \begin{bmatrix} \mathbf{L}_X \\ \mathbf{L}_Z \end{bmatrix} \Delta G_X \tag{10}$$

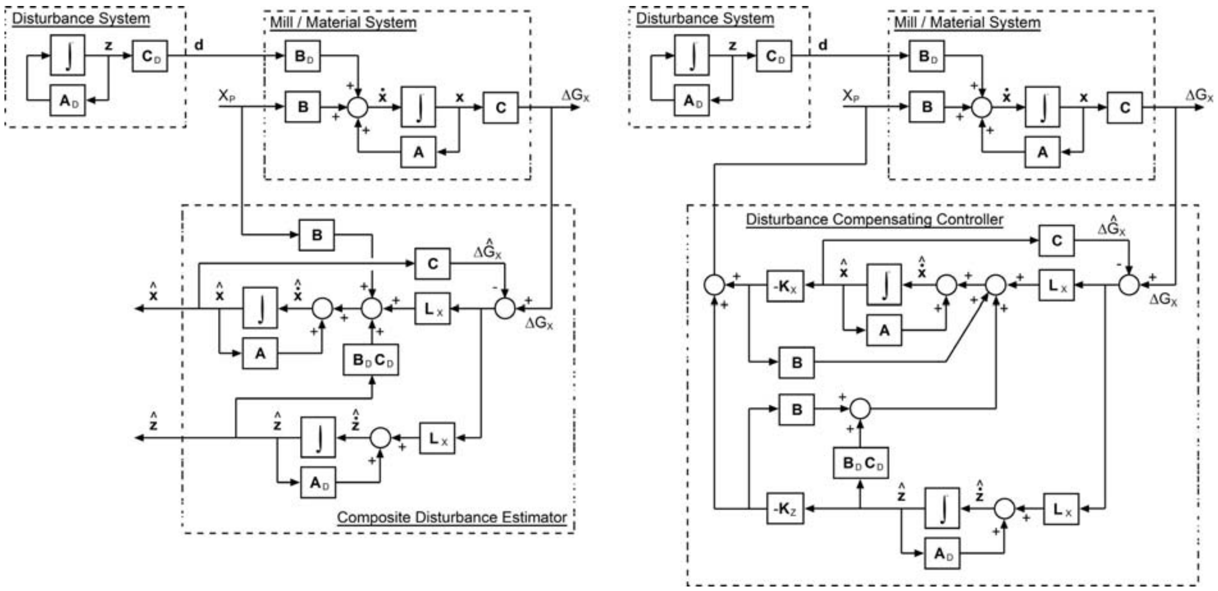
Employing these estimates within the control law of Eq(9) gives:

$$x_P(t) = -\mathbf{K}_X\,\hat{\mathbf{x}}(t) - \mathbf{K}_Z\,\hat{\mathbf{z}}(t) \tag{11}$$

The resulting closed-loop system is shown in Figure 5b and is given by:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{z}} \\ \dot{\hat{\mathbf{x}}} \\ \dot{\hat{\mathbf{z}}} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B}_D\mathbf{C}_D & -\mathbf{B}\mathbf{K}_X & -\mathbf{B}\mathbf{K}_Z \\ \varnothing & \mathbf{A}_D & \varnothing & \varnothing \\ \mathbf{L}_X\mathbf{C} & \varnothing & (\mathbf{A}-\mathbf{L}_X\mathbf{C}-\mathbf{B}\mathbf{K}_X) & (\mathbf{B}_D\mathbf{C}_D-\mathbf{B}\mathbf{K}_Z) \\ \mathbf{L}_Z\mathbf{C} & \varnothing & -\mathbf{L}_Z\mathbf{C} & \mathbf{A}_D \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{z} \\ \hat{\mathbf{x}} \\ \hat{\mathbf{z}} \end{bmatrix} \tag{12}$$

Having the structured initial conditions of $\begin{bmatrix} 0 & \mathbf{z}_0 & 0 & 0 \end{bmatrix}^T$.



(a) (b)

Figure 5. Block diagram of: a) Composite state / disturbance estimator, b) Disturbance Compensating Controller employing an internal state / disturbance estimator.

The development of the disturbance estimation and compensation controller was based on a linearized model of the mill, material, controls, and eccentricity processes local to a specified operating point. The model is an extension of the work of Huzyak and Gerber.[26] Figure 7 provides a block diagram of this model. The mill / material system matrices, $\Sigma(\mathbf{A},\mathbf{B},\mathbf{B}_D,\mathbf{C})$, are derived directly from this description. During commissioning, internal models are refined by the selection of the harmonic ranges of each roll in the stack (i.e., selection of the sets, k_{ij}, Eq(6)).

Controller adaptation is provided by the definitions of $\Sigma_D(\mathbf{A}_D,\mathbf{C}_D)$ and through least-squares recursive parameter identification techniques,[27] primarily focused on determining the instantaneous material's resistance to deformation, K_{Mill}. Using self-tuning regulator methods[27] based on entire eigenstructure assignment,[15,19,21] it is possible to recomputed the control and estimation gains, $\mathbf{K}_X$, $\mathbf{K}_Z$, $\mathbf{L}_X$, $\mathbf{L}_Z$, on-line in real-time, simultaneously providing complete pole placement with eigenvector defined response shaping.

4 CONTROLLER / ESTIMATOR PERFORMANCE STUDIES

Simulation studies have been employed to examine design techniques, performance specifications, estimator convergence criteria and activity, spatial frequency content, and to judge the exit gauge effects. Figure 6 illustrates some results of a 4-High mill

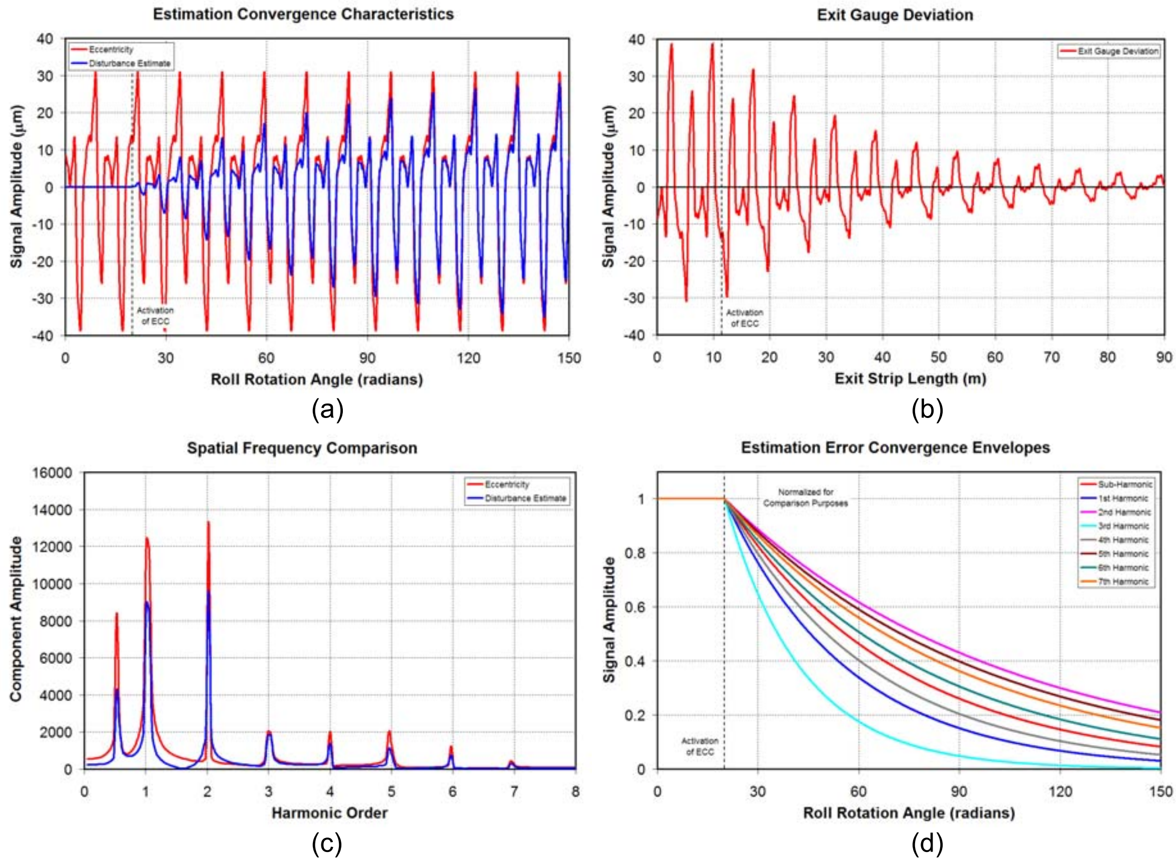


Figure 6. Simulation study results of eccentricity effects for a single defective roll (to simplify graphical content). a) Comparison of an single sub-harmonic and six (6) super-harmonic eccentricity signature to the time evolution of the composite disturbance estimate, b) Effect on exit gauge deviation, c) Spatial frequency content of the eccentricity and disturbance estimate, d) Convergence envelopes / profiles of the individual harmonic sub-systems.

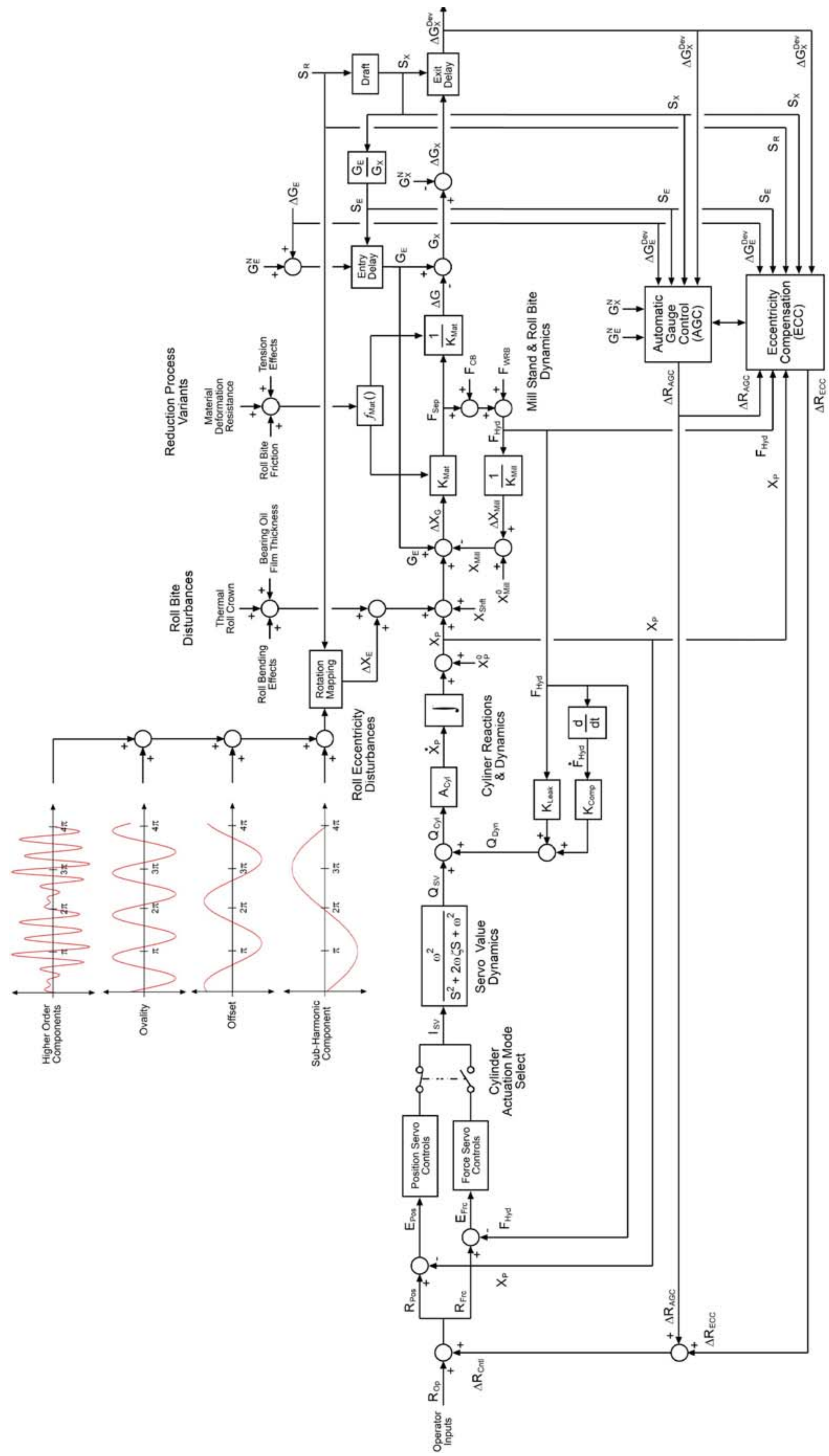


Figure 7. Block diagram of the linearized model used in the development of the eccentricity disturbance estimation and compensation controller.

study of a single offending back-up roll (to minimize example complexity) having a single sub-harmonic and six (6) super-harmonic eccentricity components. Figure 7a shows good convergence of the disturbance estimate to the roll imperfections, with the primary offending diametral variations being replicated in approximately 4-7 roll rotations. Figure 7b shows the resulting exit gauge response falling below the required 5 μm tolerance in about 50-55 meters of rolled strip. Figure 7c shows that the spatial frequency contents are similar, however, the disturbance estimator does not fully capture the entire content. It is important to note that the disturbance estimate has the same proportional peak heights for the first three components, indicating that the classical and sub-harmonic are being properly estimated, but their amplitudes are not optimal. Figure 7d shows the normalized convergence behavior of all the disturbance estimates. It is interesting to note that the 3rd harmonic shows the most rapid performance, however, its spatial frequency amplitude is relatively small, where as the 2nd harmonic (ovality) has the slowest convergence. This phenomena appears to stem from exit gauge sample spacing (length interval) as related to back-up roll diameter

5 CONCLUSION AND COMMENTARY

The disturbance estimation and feedforward cancellation approach to eccentricity compensation provides an interesting method for characterizing and attenuating a large range of harmonic components. Model / controller adaptation allows the controller to handle the typical variations found in the cold rolling process. The on-line / real-time disturbance estimates provide facility maintenance and engineering personnel insight into the mill's roll stack distortions, and can be used to diagnose and schedule roll changes and mechanical maintenance actions. The present focus of research is on providing commissioning tools that allow each roll's harmonic range sets to be automatically selected (or assisted) by on-line spatial frequency analysis.

As a final note, any application of eccentricity compensation techniques (regardless of method) is assistive, however, there is a fundamental philosophical issue that may or may not apply to a given mill or facility. In some respects, eccentricity compensation provides an automated "band-aid" solution to underlying mechanical problems. Some may employ these technologies to forego important wear and maintenance responsibilities or allow roll grinding qualities to diminish. There is a paradox where one must weigh the performance enhancement achievable by these technical means, and the value of a mechanically sound mill. Care must be taken when employing eccentricity compensation, to be sure that all efforts have been realistically made to optimize the mill's mechanical structures and roll grinding methods.

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