20-HIGH CLUSTER MILL SHAPE ACTUATOR CHARACTERIZATION THROUGH PARAMETER IDENTIFICATION METHODS[1]

Mark E. Zipf[2]

Abstract

The shape actuation systems of 20-high cluster mills have strongly coupled interactions that vary significantly over the mills' operational envelope. To support on-line, real-time shape / flatness control systems, analytic models of the mill's shape actuation behaviour have been developed. These models are also helpful in off-line studies to determine optimal mill scheduling (reduction, target shape progression, etc.) and roll profile selection. Analytic models are formed from first principles physics and often employ key assumptions intended to reduce model complexity and improve computational efficiency. This paper presents a method of direct / empirical model generation based on on-line parameter identification techniques. The initial conditions of the model parameters are set from the results of first principles mathematical models. During on-line activities, specifically tailored shape actuator input signals are injected to excite the dominant modes of the shape actuator's response characteristics, and allow the on-line parameter identification systems to capture and describe the key behavioural traits, and form the empirical model. A comparative study of nearly identical cluster mills, rolling similar materials, but having different roll cluster set-ups and operating philosophies is used to illustrate the variability of actuator's spatial influence functions.

Keywords: Shape; Flatness; Cluster mill; Mathematical modelling; Parameter identification; Automatic flatness control; AFC; Roll cluster set-up.

Resumo

Os sistemas de atuação de forma dos laminadores cluster 20-high possuem interações fortemente conectadas que variam significativamente sobre o conjunto de parâmetros operacionais dos laminadores. Para suportar on-line em tempo real, os sistemas de controle de planicidade e forma, foram desenvolvidos modelos analíticos de atuação de comportamento da forma dos laminadores. Esses modelos também são úteis em estudos off-line para determinar a programação ótima de laminação (redução, evolução da forma objetivada, etc) e seleção do perfil do rolo. Os modelos analíticos são formados a partir de princípios fundamentais de física e, muitas vezes empregam pressupostos essenciais destinadas a reduzir a complexidade do modelo e melhorar a eficiência computacional. Este trabalho apresenta um método direto/empírico de geração do modelo baseado em técnicas de identificação de parâmetros on-line. As condições iniciais dos parâmetros do modelo são definidas a partir dos resultados dos princípios fundamentais de modelos matemáticos. Durante as atividades on-line, mais especificamente, os sinais de entrada adaptados para os atuadores, são aplicados para excitar o modo dominante da resposta característica do atuador de forma, permitindo que o sistema de identificação de parâmetro on-line capture e descreva os principais traços comportamentais e a forma do modelo empírico. Um estudo comparativo de laminadores quase idênticos, processando materiais similares, mas com diferentes ajustes para os rolos e práticas operacionais, é usado para ilustrar a variedade de funções de influência espacial.

---

[1] *Technical contribution to the 47th Rolling Seminar – Processes, Rolled and Coated Products, October, 26th-29th, 2010, Belo Horizonte, MG, Brazil.*

[2] *Vice-President Control & Automation Technologies, Tenova-I2S (I2S, LLC)*

1 INTRODUCTION

20-High Cluster Mills adjust the strip's shape[1] by coordinating a set of actuators to provide corrective changes in the applied transverse pressure distribution (across the width of the roll gap) that modify the localized strip elongations, thereby altering the strain patterns, and subsequently the transverse stress / tension distribution of the rolled strip. Cluster mills have complex, highly coupled, non-linear interactions between their strip shape actuators, that result in non-intuitive control relationships that vary greatly over the operational ranges of material thickness, width, yield strength, etc.. A common actuation configuration is shown in Figure 1 and includes top crown eccentrics (B & C Backing Assemblies) and the laterally traversing, tapered 1st Intermediate Rolls (1st IMRs).

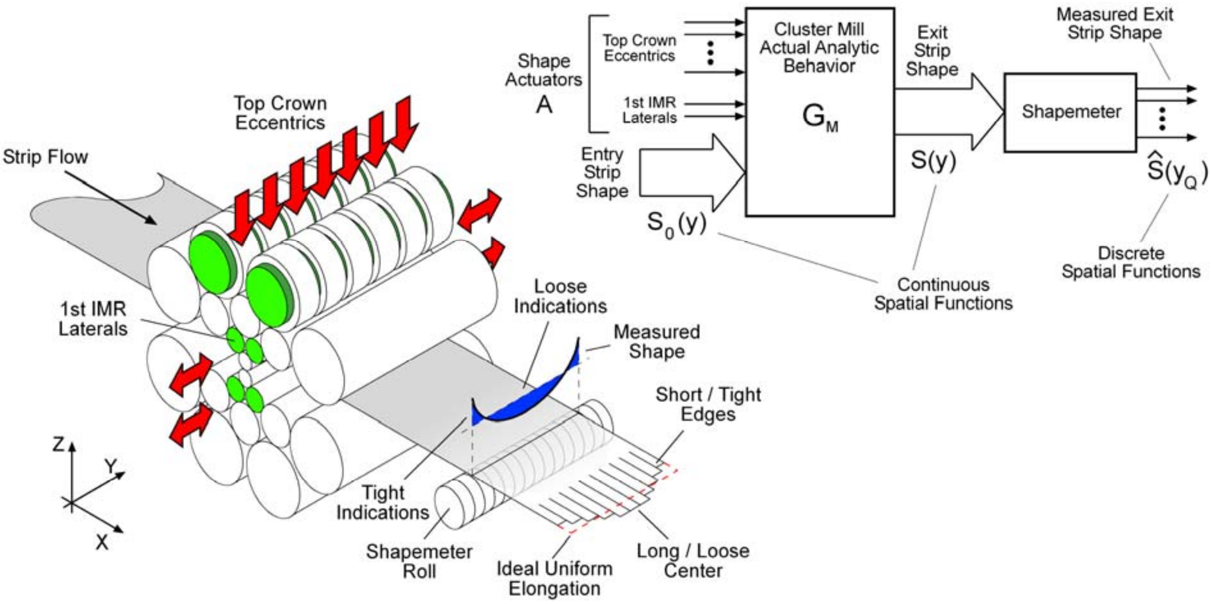


Figure 1 – Illustration of a Cluster Mill and its shape control actuators, along with a diagram showing the general form and structure of the mill's analytic description.

When changing the transverse pressure distribution in a local region, through a single actuator, the roll cluster mechanically reacts and deforms, influencing other regions of the roll bite. Therefore, each actuator induces a unique stress adjustment pattern on the strip's transverse stress distribution that can be characterized as a continuous spatial sensitivity influence function. From the ensuing roll cluster deformations, the geometry of the pattern is not localized to the vicinity of the actuator, but spans the strip width (into the regions intuitively assumed to be the domain of the other actuators). This highly coupled behaviour induces compromising interactions (like a mechanical "crosstalk") that interferes with the activities of the other actuators.

---

[1] The terms "shape" and "flatness" are often used in an arbitrary or interchangeable manner, and there are no universally accepted definitions. For the purposes of this discussion, the following terms will adhere:

Shape – The transverse distribution of differential strain / elongation induced stress within the material with respect to the material's average / nominal applied stress. This terminology implies a tensioned condition and is inherently bipolar, accounting for regions looser / longer and tighter / shorter than the nominal strip condition.

Flatness – The geometric departure of the strip from a reference plane. These distortions are associated with internal differential strain / elongation based stress patterns that exceed the material's buckling threshold, and obtain a lower potential stress equilibrium by manifesting out of the reference plane.

Multivariable control techniques [1-5] are uniquely suited for accommodating this form of non-linear, highly coupled arrangement in closed-loop shape control applications. These methods employ internal, mathematical models of the mill's actuation characteristics to render coordinated control reactions. Figure 2 provides some insight into the nature of the mill's characterizing descriptions stemming from the true continuous spatial influence functions of the strip stress and actuator sensitivities, along with the higher resolution of the shapemeter measurements, to their relationships within the discrete spatial sampling grid of the modelled behaviour.

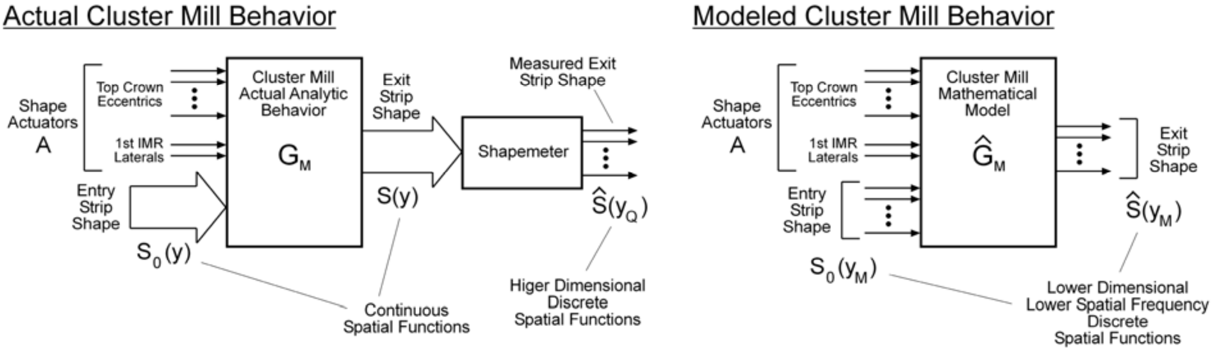


Figure 2 – Diagrams illustrating the actual Cluster Mill / Shapemeter and the Modeled Cluster Mill.

Models have been developed in a variety of ways ranging from first principle physics [6,7], to combinations of empirical and mathematical techniques [8], to sophisticated finite element analysis techniques coupled to analytic methods [9]. The accuracy, dexterity and robustness [4,5] of the models employed in control decisions is key to stable, coordinated and balanced closed-loop activities and performance. In off-line analysis of mill performance, scheduling and roll profile set-up, this same accuracy and dexterity are important in assessing mill behaviour and corrective adjustments.

Of importance, is obtaining an accurate model that spans not only the actuators' spatial sensitivity / influence function characteristics, but also properly describes variations in strip width, yield stress, tension, incoming thickness, etc. Ideally, the model would be either comprehensive or have adaptation capabilities [10], allowing it to properly describe a broad range of operating conditions.

Beyond this, the model must comply with the form and format required by the chosen multivariable control technique. In this respect, the model must not be overly complex or computationally demanding, since it must be applied within a real-time control framework.

The extent of the spatial frequencies associated with the sensitivity influence function of a given actuator is limited by the mechanical interactions within the roll cluster (e.g., roll bending, flattening, multiple contact points, etc.) and in the presence of the instantaneous strip width, yield stress, tension, incoming thickness, etc.

An important factor in model development is realizing that the spatial frequency content of each actuator's sensitivity function is dominated by lower order components. The mechanical interactions within the roll cluster do not transmit localized high spatial frequency content to the roll bite. This allows each actuator to be modelled by either piece-wise continuous vector descriptions or a collection of low order polynomials. These forms of analytic models provide the necessary level of system representation, while also accommodating the control system needs for model reduction and computational simplicity.

The foundations of many multivariable shape control methods, applicable to cluster mill configurations [1,2,3], are based on decompositions of the potentially complex transverse strip stress and actuation patterns (described by an internal model derived from the spatial sensitivity functions). These approaches can range from orthogonal polynomial based curvature spaces [1,2,3] to Singular Value Decomposition (SVD) [4] to optimal predictions of future mill responses using Model Predictive Control (MPC) [11].
Regardless of the multi-variable control approach used, the underlying internal models is still the same.
This work examines the use of direct / empirical model generation based on on-line parameter identification techniques [10,12]. The initial conditions of the model parameters are set from the results of first principles mathematical models. During on-line activities, specifically tailored shape actuator input signals are injected to excite the dominant modes of the shape actuator's response characteristics, and allow the on-line parameter identification systems to capture and describe the key behaviour traits. The resulting model is applied to the multi-variable shape controller (as an internal model) to form a self-tuning regular. This arrangement is shown in Figure 3.

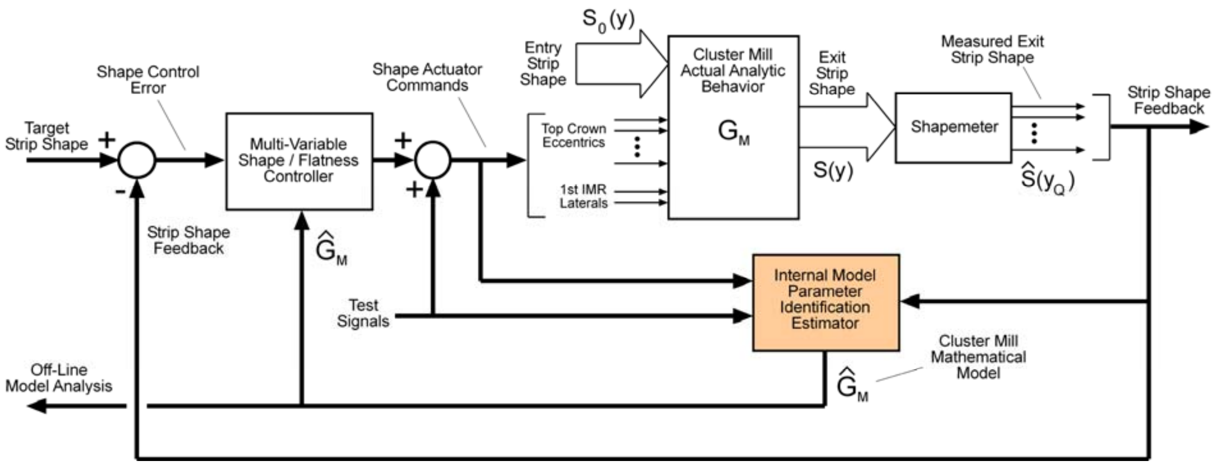


Figure 3 – Diagram of the parameter identification embedded in a closed-loop shape control system.

2 OVERVIEW OF MILLS, SYSTEMS AND OPERATIONS

2.1 ZR23CN-26 20-High Cluster Mills

Three (3) highly similar mills where considered in this evaluation. Although nearly identical in design and manufacture, each mill was scheduled, roll cluster set-up and operated in subtly different manners that reflected facility specific, long held, historic operating philosophies. Table 1 provides a numerical designation and tabular listing of the key parameters that define and characterize each mill.
The key differences in the mill set-up and operations are as follows:

1) Mill 1 was operated with flexible backing assemblies and a solid top idler roll. Mill 2 was operated with a combination of flexible and solid backing assembly shafts (primarily solid), and solid top idler roll. Mill 3 was operated with flexible backing assemblies and a segmented top idler roll.

2) Mill 3 had a larger wrap angles on the shapemeter roll, tending to suggest that more accurate shape measurements were rendered (over the measurements of Mills 1 and 2)

Table 1 – Tabular listing of the defining parameters that characterize the mills considered in this evaluation. Highlighted entries indicate mill-to-mill differences of importance

Designation	**Mill 1**	**Mill 2**	**Mill 3**
Mill Type	ZR23CN-26		
Crown Eccentrics	Seven (7) Hydraulically Actuated		
1st IMRs	Hydraulically Actuated - 100mm Stroke		
1st IMR Tapering	One(1) Step	Two(2) Step	Two(2) Step
Work Roll Diameter Range	40.2 - 59.4mm	40.2 - 59.4mm	31.6 - 48.5mm
Top Idler	Solid	Solid	Segmented
Backing Assembly Shaft	Flexible	Solid / Flexible	Flexible
Shapemeter Roll	T. Sendzimir with 20 Segments		
Shapemeter Wrap Angles	0.65-2.9 deg	0.65-2.9 deg	1.8-4.3 deg
Product Mix			
Alloys	Stainless Steel - 300 & 400 Series		
Width Range	375-650mm	350-600mm	375-650mm
Gauge Range	0.050-3.00mm		
Transverse Profiles	Asymmetric	Symmetric & Asymmetric	Asymmetric

3) Mill 1 employed a single step 1st IMR tapering philosophy, while Mills 2 and 3 employed two (2) step tapers.
4) Mill 2 typically operates on narrower products (both in symmetric center-cut and asymmetric / wedged side-cut arrangements), however a sufficiently broad region of product width overlap was available to conduct the experiments.

2.2 Mill Systems

The control, automation and drive systems on all three (3) mills were nearly identical [13]. A PLC serves as the mill's Master Controller and provides the closed-loop servo controller for the Top Crown Eccentric and 1st IMR Lateral Traverse actuators. A shapemeter roll provides measurements of the transverse tension distribution. Identical shapemeters are mounted on both sides of the mill (entry and exit shape measurements). The remotely measured forces are signal conditioned and network transmitted to the AFC for further processing and determination of the I-Unit shape. An IBA data acquisition system provides real-time measurements of all equipment activities, rolling condition, test signals and resulting model parameters.

3 SYSTEM IDENTIFICATION METHODOLOGY

Experimental / empirical identification of the mill actuators' spatial sensitivity influence functions was provided by employing differential perturbation methods involving the transverse dynamic response characteristics of the rolled and measured entry / exit strip shape to individual actuator excitation. The probative system identification signals involved low amplitude, bipolar, zero mean, colored noise waveforms designed to provide the necessary excitation of the individual actuators and to be easily deconvolved from the shape controller's actuator commands and from the resulting strip shape adjustments. The signals were also designed to not affect the shape performance or distract the shape control system.

The probative signals were injected into both the mill actuation and an analytic simulation model to render both an actual response and a model predicted response.

These responses were processed to generate a high spatial frequency description of each actuator’s spatial influence function (at the resolution of the shapemeter measurements). An on-line recursive least squares fitting algorithm was used to approximate the spatial influence functions (in polynomial representations) as a continuous function of the strip width. The resulting polynomials were evaluated (re-sampled) at grid spacing in accordance with the multivariable actuator space (9 total actuators), to generate lower spatial frequency vectoral representations that directly formed the model. Figure 4 provides a block diagram of this approach. Figure 5 illustrates the time series reactions to a simplified probative signal.

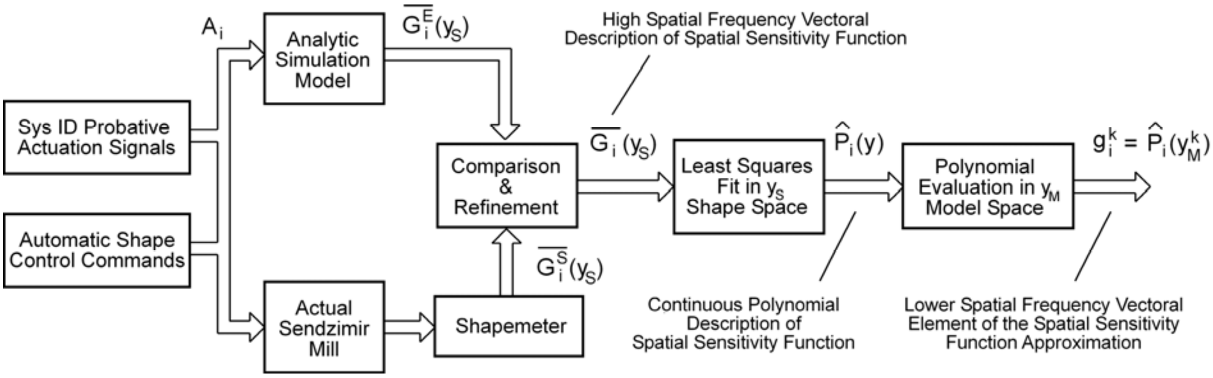


Figure 4 – Block diagram of the internal model development process.

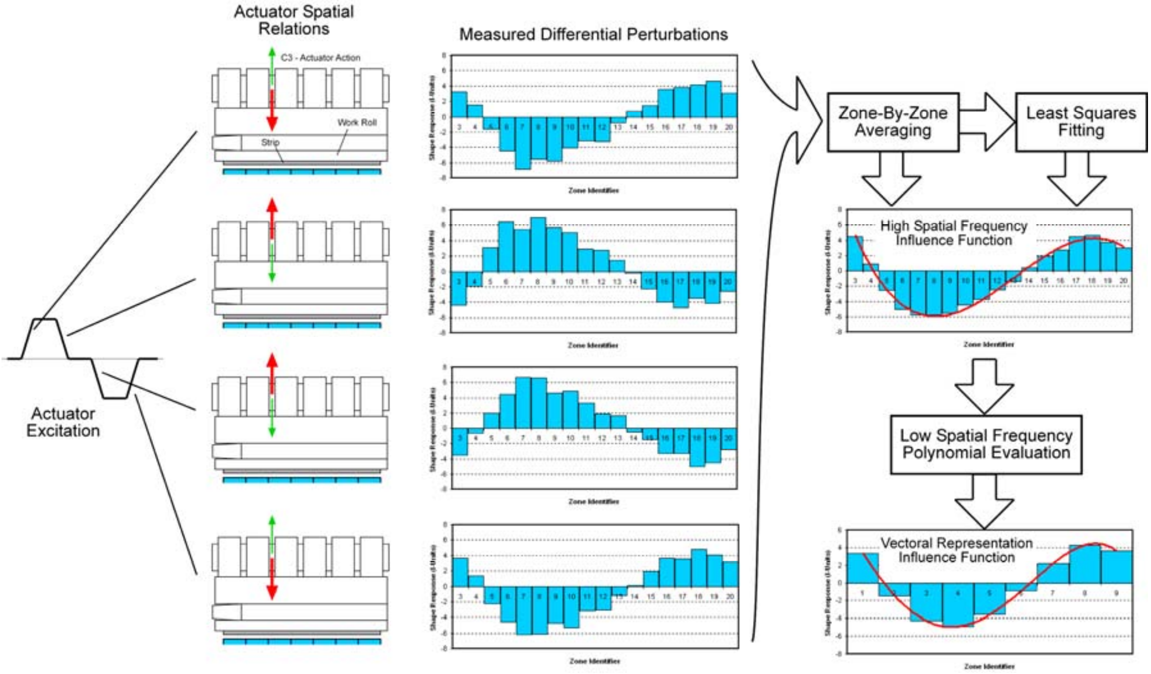


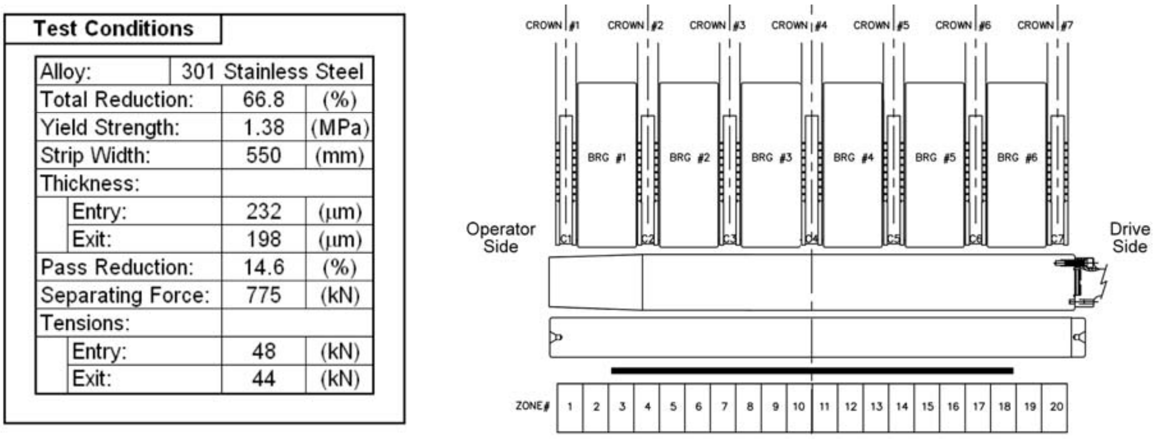
Figure 5 – Time series diagram of the parameter identification process applied to a simplified probative signal applied to Crown #3.

4 COMPARISON OF MILL RESPONSE CHARACTERISTICS

The parameter identification process was performed on the three (3) mills under consideration, over their general product mixes and operating conditions. The resulting influence functions were collected and compiled into a data base for further analysis and comparative studies.

The studies involved direct, zone-by-zone comparisons of the mills’ high spatial frequency influence functions on nearly identical materials (same width, thickness, yield strength / total reduction, etc.), while the mills were rolling under similar pass conditions (i.e., reduction, separating force, tensions, speeds, etc.). Due to the subtle variations in the individual mill's 1st IMR taper conventions, roll grinding, roll cluster set-ups, and operating philosophies, it was decided that the high spatial frequency influence functions where the best choice of comparative analysis, since they would expose the higher order, transverse spatial dynamics of the individual mills.

Figure 6 provides a listing of the test conditions, including a scaled diagram showing the ZR23CN-26 cross-section geometry and relation to the strip width / location.



Test Conditions

Alloy:	301 Stainless Steel	
Total Reduction:	66.8	(%)
Yield Strength:	1.38	(MPa)
Strip Width:	550	(mm)
Thickness:		
Entry:	232	(µm)
Exit:	198	(µm)
Pass Reduction:	14.6	(%)
Separating Force:	775	(kN)
Tensions:		
Entry:	48	(kN)
Exit:	44	(kN)

Figure 6 – Example test conditions and scaled illustration of the mill cross-section related to the strip.

Due to the inherent folded center-line symmetry of the mills' actuators (about Crown C4), only the first four (4) top crown eccentrics and the top / front 1st IMR actuator influence functions will be presented (i.e., we will consider only operator-side crowns C1, C2, C3, the center crown C4, and the operator-side influencing top 1st IMRs).

Figure 7 provides series of plots showing a comparison of the measured actuator influence functions for the test conditions described in Figure 6. The overlay plots of the influence functions have all been mapped to a normalized strip width space, instead of a zonal space, to compensate for off centered strip. In all cases, the edge zones were partially covered and edge zone coverage compensation was applied to incorporate all available zones.

5 FINDINGS AND DISCUSSION

The actuator influence functions shown in Figure 7 illustrate that although the mills and rolled materials are essentially identical, the mill's shape actuation behavior has notable differences. Recalling the mill characterizations of Table 1, the individual mill's roll cluster set-ups are different and these subtle idiosyncrasies contribute to the measured variations.

5.1 Crown #1 Results (Figure 7a)

These indications suggest that the presence of the flexible backing assemblies and segmented idler roll channel (Mill #3) direct Crown #1's actuation pressures into more localized, higher spatial frequency regions of the strip edge, and also a low drive-side reactions. Since "stiffer" configuration (Mill #2) is more tightly coupled, its Crown #1 actuation is distributed further across the transverse strip width, thereby applying a greater magnitude of pressure local to the strip edge.

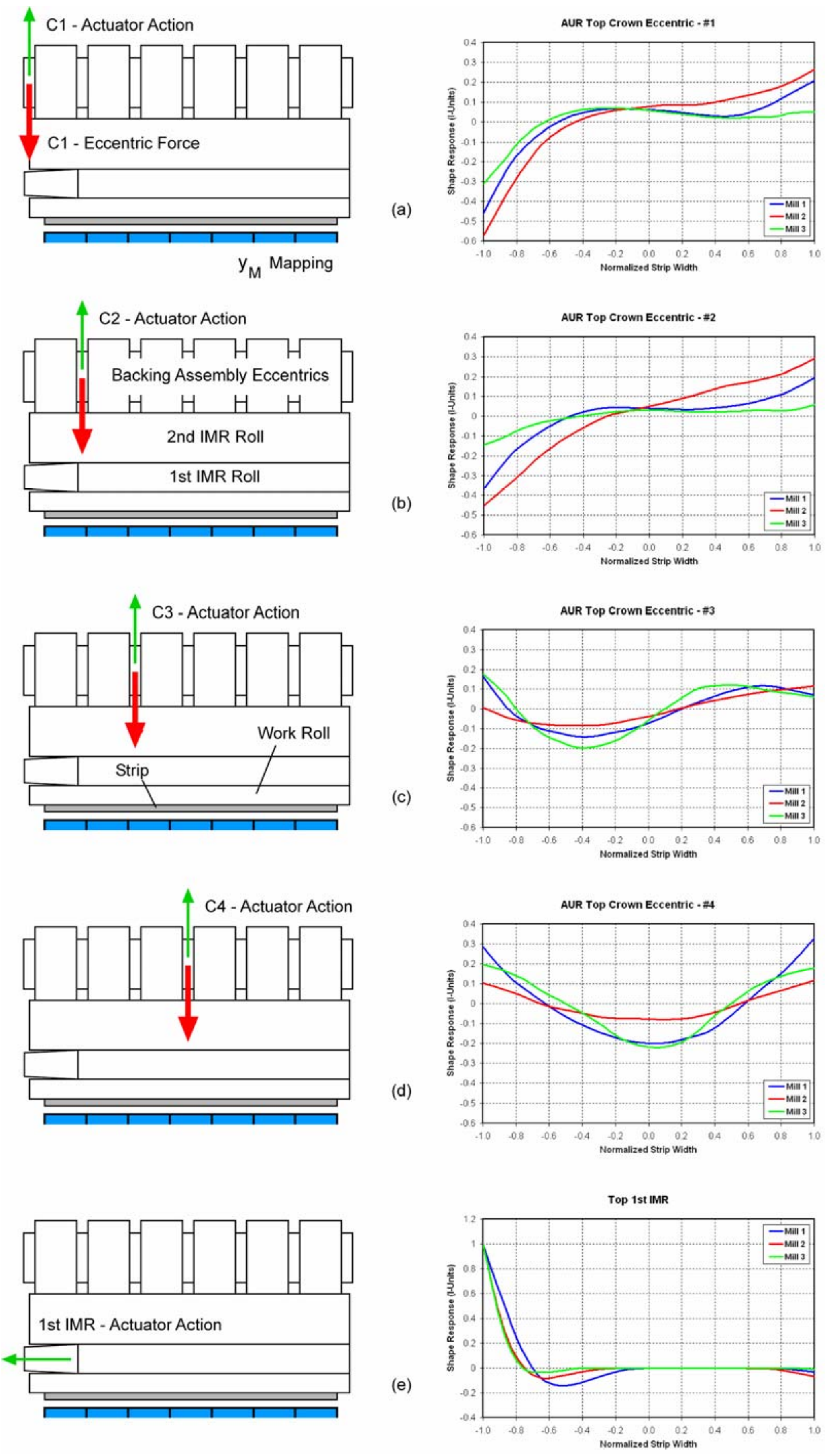


Figure 7 – Comparison of three (3) mills' shape actuator influence functions.

5.2 Crown #2 Results (Figure 7b)

As shown in Figure 6, the Crown #2 actuator resides just over the operator-side edge of the strip. Like Crown #1, Crown #2 induces a strong operator-side, loosening reaction, but of lower amplitude. The stiffer Mill #2 presented an almost linear, levering response, with a fulcrum near the center of the strip. Mill #1, with its flexible backing assemblies, had a very similar, but lower amplitude response. The highly flexible Mill #3 provided an interesting response. Its localized Crown #2 pressure distribution only affected the strip edge, with a transverse characteristic being almost flat. This indicates that the flexibility of Mill #3 achieved an equilibrium condition without requiring the roll cluster to distort to find an equilibrium.

5.3 Crown #3 Results (Figure 7c)

All the mills possess a similar influence function, but they differ by the degree of spatial frequency. All induce a loosening effect local to the vicinity of the Crown #3 geometry. All cause the roll cluster to deflect and bow in reaction to the actuator’s localized pressure distribution, with a tightening of the operator and drive side regions. The stiffer Mill #2 imparts a rather broad, low spatial frequency transverse response, due to its lack of flexibility, which distributes and attenuates the applied pressure across the mill’s width. The flexible backing assemblies in Mill #1 induce a narrower, more focused pressure distribution, which produce a stronger shape adjustment in the vicinity of Crown #3. Crown #3 in the highly flexible Mill #3 produced the narrowest and highest amplitude local reaction.

5.4 Crown #4 Results (Figure 7d)

The application of the Crown #4 actuator causes the roll cluster to deflect and symmetrically bow in reaction to the actuator’s centralized location, with nearly identical tightening of the operator and drive side regions. This actuator (along with Crown #3), provides the best indications of the relative differences between the various mill configurations. The “stiffer” Mill #2 imparts a rather broad transverse response, due to its lack of flexibility, which distributes and attenuates the applied pressure across the mill. The flexible backing assemblies in Mill #1 induce a narrower, more focused pressure distribution, which produce a stronger shape adjustment at the strip center. The highly flexible Mill #3 produced the narrowest and highest amplitude local reaction. It is interesting to note the strip edge reactions of the more flexible Mills #1 and #3. Mill #1’s tightening effects are much larger than those measured for Mill #3. It appears that Mill #3’s segmented idler roll may assist in the attenuation of the spread of Crown #4’s pressure distribution.

6 CONCLUSION

The findings shown in this paper are but a small percentage of those determined in this study. All of the obtained results have led to similar conclusions about the various mill’s behaviors and the underlying origins of these response characteristics.
The primary interest has been to empirically characterize the shape actuation reactions of similar, but subtly different mills to assist in improving analytic models and multivariable shape control techniques. The finding of this study are being used to validate and improve the analytic models to provide improved prediction

capabilities when assisting in the resolution of complex strip shape issues (i.e., roll grinding and roll cluster set-up mistakes and / or misunderstandings). To this extent, the results of this study have been very valuable.

A crucial concern not addressed in this study, is whether the use of flexible backing assemblies and a segmented top idler roll will provide a higher caliber of overall shape control and actuator coordination stability [14]. Yes, the narrower, higher spatial frequency influence functions of the flexible components provide a more directed “attack” on localized shape disturbances, however, they also induce odd coupled transverse reactions in the roll cluster. The Mill #3 spatial responses local to Crown #3 (Figure 7c) is highly desirable, but the nearly symmetric counter reaction on the opposing side of the strip center-line must be offset by the coordinated efforts of other actuators (all within the actuation constraints – Crown Step Limits, etc.).

The stability characteristics and margins of these different mill configurations (especially when rolling strip having an asymmetric / wedged profile), is a focus of on-going research and interest.

REFERENCES

1 Grimble, M.J., Fotakis, J., **The Design of Strip Shape Control Systems for Sendzimir Mills**, IEEE Transactions on Automatic Control, Vol. AC-27, No. 3, pp 656-666, June 1982.

2 Ringwood, J.V., **Shape Control Systems for Sendzimir Steel Mills**, IEEE Transactions on Control System Technology, Vol. 8, No. 1, pp 70-86, January, 2000.

3 Ringwood, J.V., Grimble, M.J., **Shape Control in Sendzimir Mills Using Both Crown and Intermediate Roll Actuators**, IEEE Transactions on Automatic Control, Vol. 35, No. 4, pp 453-459, April 1990.

4 Ringwood, J., **Multivariable Control Using The Singular Value Decomposition In Steel Rolling With Quantitative Robustness Assessment**, Control Eng. Practice, Vol. 3, No. 4, pp 495-503, 1995.

5 Bates, D.G., Ringwood, J.V., Holohan, A.M., **Robust Shape Control In A Sendzimir Cold-Rolling Steel Mill**, Control Eng. Practice, Vol. 5, No. 12, pp 1647-1652, 1997.

6 Gunawardene, G.W.D.M., **Static Model Development for the Sendzimir Cold Rolling Mill**, Ph.D. Dissertation, Sheffield City Polytechnic, 1982.

7 Guo, R.M., Malik, A., **Development of New Crown / Shape Control Model for Cluster Mills**, AIST Conference Proceedings, Nashville, 2004.

8 Zipf, M.E., Godwin, C.K., Wisti, D.R., **Modeling and Simulation of Sendzimir Mill Shape Control Actuation Sensitivities and Capabilities Envelope with Applications to Multivariable Shape Control**, Proceedings of the Associação Brasileira de Metalurgia e Materiais, 43rd Rolling Seminar – Processes, Rolled and Coated Products, October 17-20, 2006, Curitiba, PR, Brazil, Compact Disk (CD) pp 856-866.

9 Malik, A.S., Grandhi, R.V., Zipf, M.E., **Optimal Cluster Mill Pass Scheduling With an Accurate and Rapid New Strip Crown Model**, Proceedings of the NUMIFORM ‘07, the 9th International Conference on Materials Processing and Design: Modeling, Simulation and Applications, June 17-21, 2007, Proto, Portugal, American Institue of Physics, pp 1041-1046..

10 Astrom, K.J., Wittenmark, B., **Adaptive Control**, Addison-Wesley, Reading, 1989.

11 Karim, M., Tarek, K.M., **Predictive Functional Control of a Sendzimir Cold Rolling Mill**, Proceedings of the 4th International Conference on Computer Integrated Manufacturing, November 3-4, 2007..

12 Ljung, L., Soderstrom, T., **Theory and Practice of Recursive Identification**, MIT Press, Cambridge, 1983.

13 Zipf, M.E., Elwell, T.G., Godwin, C.K., Wisti, D.R., Hummel, C.F., **A Cost Effective Automatic Shape / Flatness Control System**, AISE Steel Technology Magazine, pp. 48-55, November / December Issue, 2003.
14 Anderson, B.D.O, et.al., **Stability of Adaptive Systems**, MIT Press, Cambridge, 1986.