# OUTPUT THICKNESS AND ROLLING FORCE MODELS IN COLD ROLLING STEEL

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***Abstract.*** *The stands rolling mill governing equation are non-linear function on several parameters (input thickness, front and back tensions, yield stress and friction coefficient among others). Any alteration in one of them will cause alterations on the rolling load and, consequently, on the outgoing thickness. In this study a physical model has been used to predict output thickness and rolling force in cold rolling. The parameters required by the model have been determined from measured rolling parameters in CSN Tandem cold rolling mill with 5 stands. Measured data of several coils have been used in the model system identification, e.g. ARX model or Box Jenkins model for cold rolling mills process. The calculated results were in good agreement with measurements and system identification theories.*

***Keywords:*** *Cold rolling, System identification, modeling and simulation*

## 1. INTRODUCTION

This paper is organized in five sections: In the first section, the representation of the cold rolling process in the LTF#3-CSN. In the second section, the work developed is explained. In the third section, any results obtained with experimental data are presented. In the fourth section, the system identification predictive model will be presented. Finally, simulation results will be discussed.

## 2. COLD ROLLING PROCESS IN THE LTF#3-CSN.

The Tandem cold Rolling mill number 3 (LTF#3) of CSN it is a four high mill of 5 stands "described by Dias *et al.* (2005)", Figs. 1 and 2 and Tab.1. The LTF#3 had its operation started in 1982, projected for a capacity of 1.500 Million annual tons and maximum rolling speed of 1890 m/min. Nowadays, LTF#3 is the only supplier of coils " full-hard " for the flows of galvanized products and of cold line of CSN-Volta Redonda and GALVASUD, therefore, production interruptions not planned and quality defects in LTF#3 will affect the provisioning and quality of those flows directly.

**Table 1 Data of Tandem Cold rolling Mill LTF#3-CSN**

| Mill type | | 5-stand tandem cold mill, all stands hydraulic screw-down 1 to 5 stands: 4-high mill | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Roll size | | Witdh: 1200 mm | | | | | | |
| | | Work roll | | Backup roll | | | | Obtained Reduction % |
| | | | | Diameter (mm) | | Weight (kN) | | |
| | | diameter (mm) | Weight (kN) | Top | Botton | Top | Botton | |
| | Stand # 1 | 538 | 50,924 | 1.400 | 1.410 | 323,227 | 325,536 | 24 |
| | Stand # 2 | 577 | 54,615 | 1.410 | 1.455 | 325,536 | 335,925 | 23 |
| | Stand # 3 | 571 | 54,047 | 1.384 | 1.426 | 319,533 | 329,230 | 17 |
| | Stand # 4 | 522 | 49,409 | 1.460 | 1.465 | 337,080 | 338,234 | 14 |
| | Stand # 5 | 570 | 53,952 | 1.484 | 1.515 | 342,621 | 349,778 | 3 |

The thickness variations in the metallic foils and cold strip are known problems and reason of study in steel plants of every world. That defect is unacceptable in the cold rolled products to applications as white line and automobile industry, among other.

In LTF#3 - CSN, that defect would cause: i) Loss in the attendance the delivery date to the customer due to the deviation of the original order; ii) Increase of the production costs with the flow change for use of the material and iv) Reduction of the cold rolling speed (action to eliminate the defect).

The output thickness and Rolling force in each stand rolling mill, Fig. 2, are given as in the work of "Gouvêa *et al.*(2002)", is governed by a non-linear function on several parameters, Eq. (1), as described several researchers as "Alexander (1972)", "Roberts (1978)", "Hasegawa and Taki (1991)", "Freshwater (1996)", "Gonçalves and Helman

(1998)", "Zárate et al.(2003)", "Zárate (2005)", where: E: Young modulus roll; R: Roll radius: W: Strip width and M: Stiffness Rolling Mill modulus. The output thickness also influenced by the strip interstand tensions, that are shown in the Fig. 3. If there are any alterations on either of them: input thickness ($h_i$), foward ($t_f$) or back ($t_b$) tensions, average yield stress $(\bar{y})$ or friction coefficient ( $\mu$ ), that may occur due to several causes as presented in "Beal (2007)", Fig. 4, They will cause alterations on the rolling load ($P$) and. consequently on the output thickness ($h_0$).

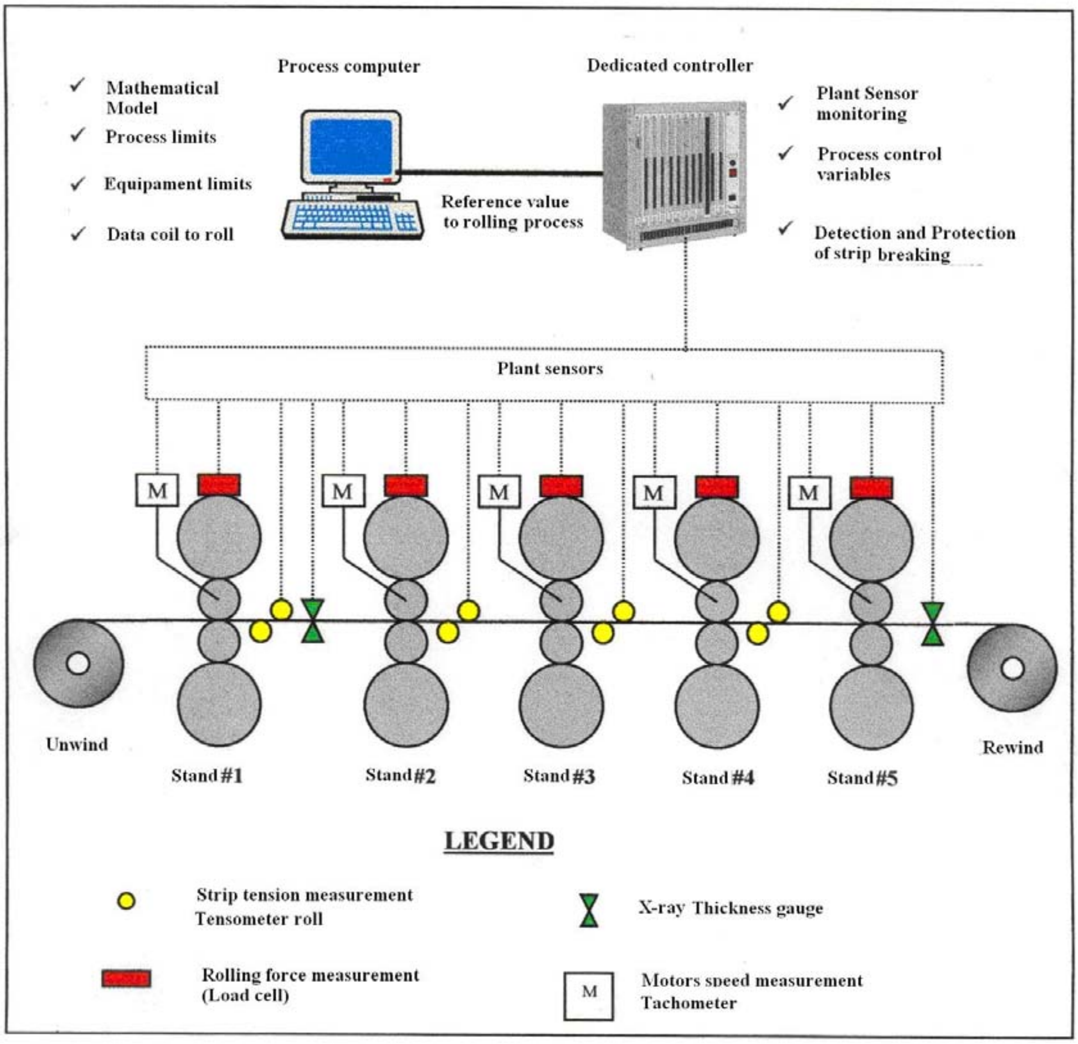


Figure 1. Schematic diagram of the LTF#3-CSN

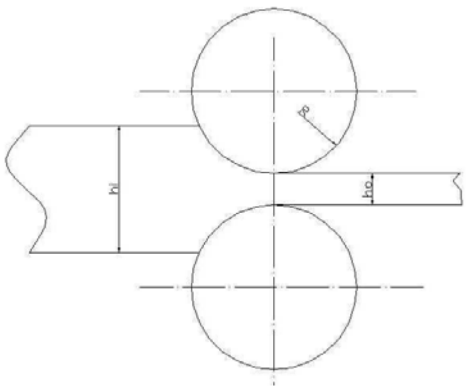


Figure 2. The input and output thickness in each stand rolling mill

$$(h_o, P) = f(h_i, t_b, t_f, \mu, \bar{y}, E, R, W, M) \quad (1)$$

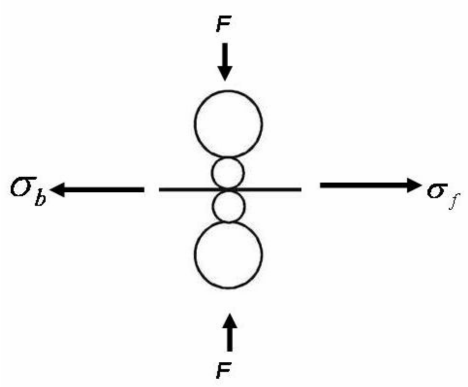


Figure 3. The strip interstand tensions in cold rolling mill

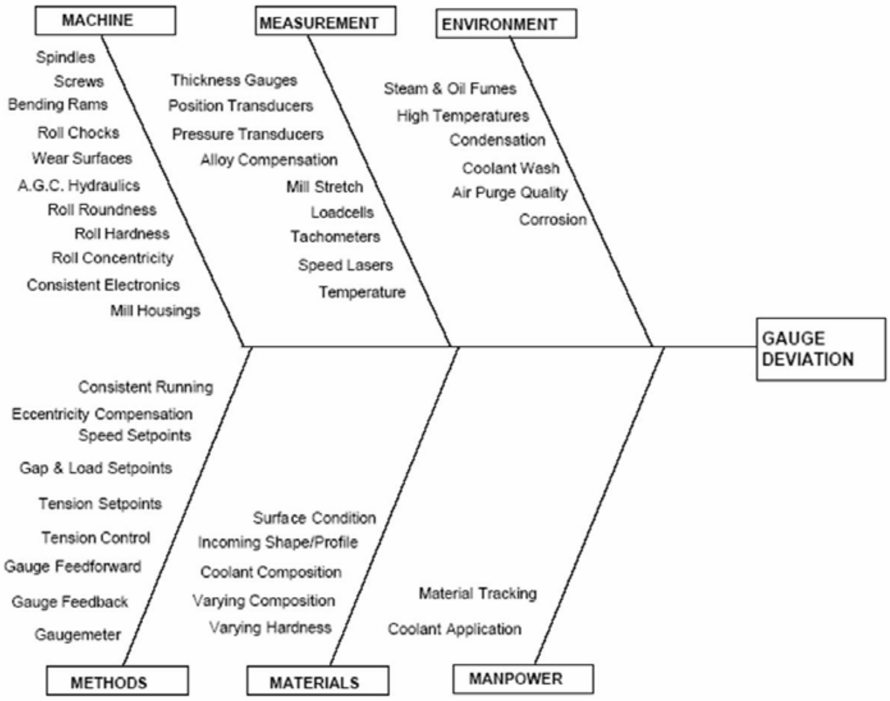


Figure 4. Rolling Mill Gauge Deviation: Probable Cause & Effect Diagram

If the early mentioned alterations occur in the rolling process, three control parameters are mainly used to restore the output thickness, ensuring the condition $\Delta h_o = 0$; the roll gap, the front and back tensions. The best control parameters will restore the output thickness for its nominal value with the smallest possible adjustment.

The Automatic Gage Control (AGC) system for output thickness control applied is basically an AGC system as described in "Wallace (1964)"; "Hisikawa (1990)" and "Ferreira (2000)", that is a feedback control system applied to rolling mills to ensure that output strip thickness will be as constant as possible. To measure the thickness deviations two techniques have been extensively used in the LTF#3 CSN:

a) In the first and fifth stands include a sensor (X ray) located after the roll gap. That may to cause a time delay in the feedback system.

b) In the second, third, fourth stands the second technique indirectly calculates the output thickness from the measurement of the roll force. This technique presents problems for thin strips, because variation in the strip thickness have little effect on the measured roll force as in the works of "Zárate and Helman (1999)", "Zárate. (2000)" and "Zárate. (2005)".

The developed work in this paper had as main objective to model the cold rolling process looking for the prediction of thickness variations, and then may change the process and to keep uniform the strip thickness, ensuring the necessary quality attendance to the cold rolled products and the production attendance for provisioning of the front lines of the cold Rolling mill. The domain about the main factors that provide the strip thickness variation was also one of the objectives.

**3 MATERIALS AND METHODS**

This work was developed using acquired data experimental during the normal operation of the Tandem cold rolling mill LTF#3 of CSN, the analytical modeling, the systems identification techniques and the subsequent analysis of the obtained results.

The action sequence used in the conduction in this work it was:

1. material main parameters identification of the strip to be cold rolled;
2. final product main parameters identification (cold strip );
3. tool main parameters identification (Tandem cold roling mill, LTF#3 CSN);
4. Cold rolling process parameters identification;
5. Data acquiring of the close to the equipment and to the process;
6. Data experimental Preprocessing;
7. Process Analytical modeling;
8. Process modeling by system identification technique;
9. Results critical analysis.

The data experimental acquiring was realized through existent instrumentation in the cold rolling mill:

Load Cells for rolling force measurement;
Sensor for torque measurement in the cold rolling mill motors;
Work roll angular speed tachometer;
Ray X Gauger for strip Thickness Measuring
Position Transducers for work roll opening measurement (gap);
Meter of acceleration and unaccelaration of the rolling mill;
Tensiometer for interstands tension measurement;
And others sensor of the rolling mill.

Those data experimental were acquired with sampling time of 0,020 seconds that is in agreement with the main references of sampling time for cold rolling process and also it assists the of the systems identification objectives.

It was prioritized in this work the use of linear models in the system identification with objective of finding simpler models to describe the cold rolling process by sampled parameters. This procedure was adopted for each stand of the Tandem cold rolling mill LTF#3 CSN, that allowed to find results as shown to proceed.

The thickness variations in the metallic foils and cold strip are known problems and reason of study in steel plants of every world. That defect is unacceptable in the cold rolled products to applications as White Line and Automobile Industry, among others.

The cold rolling mill operators have available a graphical interface with the main parameters of cold rolling, e.g. the interface presented in the "work of Pfeiffer (2006a)" that use Unit British system as shown in the Fig. 5.

The steel cold rolling basics sequence are following:

A. The main cylinder control loop typically should run every millisecond. A conventional cylinder control loop will:

1. Read and scale the position transducer signals to generate an average position for each cylinder. The transducers may be checked for reality etc. and any discrepancy alarmed. Depending upon software switches (status of logical variables) the average position may be derived from one transducer or both position transducers per cylinder. Cylinder and stack tilt variables are calculated, compared against a reference and any discrepancy alarmed.
2. Read and scale roll force transducers. These will be, at a minimum, roll load cylinder pressure transducers and, if fitted, load cells. Differential and total values are calculated. Dependent upon software switches (status of logical variables) either pressure transducers or load cells may be used for control and/or indication of roll force.
3. Compute a cylinder position error by subtracting each cylinder average position from a cylinder position reference. This error signal is multiplied by a cylinder position loop gain value. Note that the cylinder position reference is derived using other (slower) control loops. For the case of Gauge Error Feedforward Correction and Backup Roll Eccentricity Compensation, the correction values add to the cylinder position reference prior to development of the error signal.
4. Compute a cylinder roll force error by subtracting each cylinder force from a cylinder roll force reference. This error signal is multiplied by a cylinder roll force loop gain value. Note that the cylinder roll force reference is derived using other (slower) control loops. Any Gauge Error Feedforward Correction is handled in the same way as it is in the position loop.
5. Dependent upon whether roll force or position control is selected, the requisite error signal is taken and multiplied by the square root of the pressure drop across the servo valve to produce a servo valve flow signal. (Bernoulli's equation).
6. The servo valve flow signal is used to generate a servo valve reference that will be output to the servo valve control card(s). A servo valve offset value is added to the servo valve reference to account for any leakage across the servo valve. The offset value is calculated by slow accumulation, (integration), of the servo valve flow signal and is zeroed when the cylinders are vented. The offset is checked against limits and extraordinary values alarmed. Where multiple servo valves are available, selection and any cascade control is performed. Note that when cylinder vent is selected each servo valve is forced to a full vent position.
7. If the cylinder control loops are performed by a single board processor, there is usually some kind of processor healthy or heartbeat type clock that may be used by the rest of the system.

B. Gauge Error Feedforward loops usually are arranged to be interrupt driven from entry strip speed. At maximum entry speed, the feedforward loop will be operating every millisecond. The loop consists of:

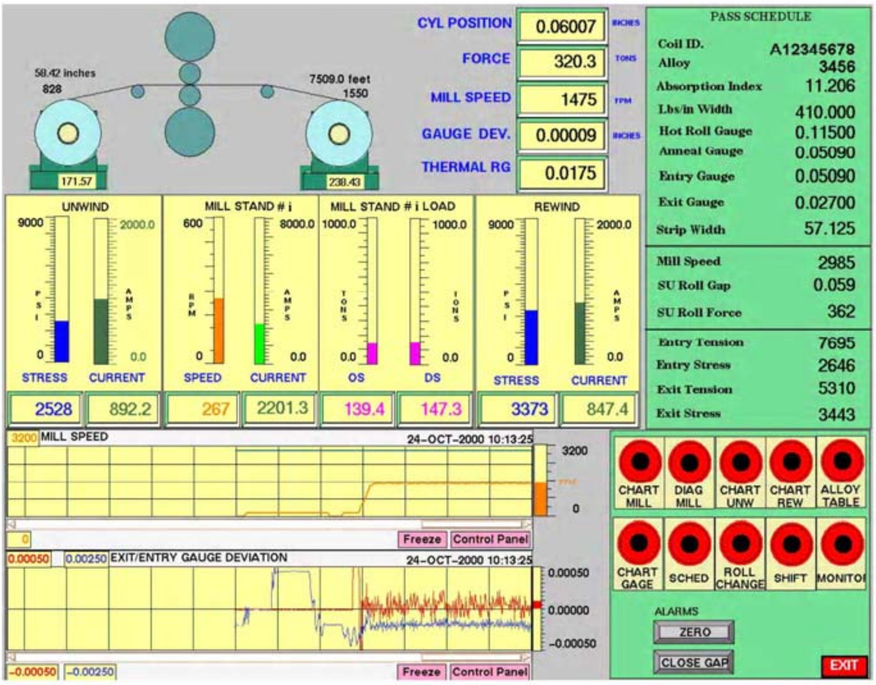


Figure 5. Example of the cold rolling mill operators interface

1. Reading and scaling the entry gauge deviation. Inserting the new data into the delay line;
2. Calculating a material stiffness gain factor for Feedforward correction;
3. Extracting an appropriately delayed entry gauge deviation, multiplying by the material stiffness gain factor and multiplying by a "Feedforward gain value" and checked against limits.
C. Depending on the method of calculation, the Backup Roll Eccentricity Compensation algorithms may be synchronized to backup roll revolutions. Loop time is usually arranged to be about 1 millisecond at the fastest backup roll revolutions;
D. Cylinder position control loop reference generation and cylinder roll force control loop reference generation usually run of the order of every 10 to 20 milliseconds, (typically 10 ms) and usually include:
1. Gaugemeter mill stretch feedback. This includes anticipated mill stretch and all of the methods of varying the conversion of roll force into mill stretch, including mill stiffness gain factors;
2. Mill zero logic. This may be complicated by screw referencing logic;
3. Gap setting: includes addition of all corrections except Feedforward and Backup Roll Eccentricity Compensation that make up the cylinder position and roll force references. Includes mill level or steer control;
4. Control logic: a state machine approach seems to work best and is easily documented for the different modes of operation.
E. The Gauge Error Feedback control loop typically may run every 50 - 100 milliseconds. It comprises
1. Reading and scaling the exit gauge deviation signal;
2. Calculating the material stiffness gain;
3. Calculating a speed dependent gain;
4. Calculating a corrected deviation error signal by multiplying the exit gauge deviation by the material stiffness gain and by the speed dependent gain;
5. Selecting an integral gain dependent upon the modulus of the corrected deviation error signal.
6. Performing the integrator function using the previously selected gain.
F. Backup roll bearing oil film compensation when Morgoil backup roll bearings are used on the mill. This loop runs every 50 to 100 milliseconds. Data is obtained in graphical form from Morgan Construction Co, Worcester MA.
G. Speed effect compensation: typically every 50 or 100 milliseconds. Means producing a reference that causes the roll gap to open as the mill is accelerated. Involves a material stiffness calculation and multiplying by a gain factor.

## 4. SYSTEM IDENTIFICATION

### 4.1. Defining model structures

Since the System Identification handles a wide variety of different model structures, it is important that these can be defined in a flexible way. The models are automatically produced in the right form by the various estimation routines arx, iv4, oe, bj, armax, and pem, if you just specify model orders and delays.

This section describes how model structures and models can be directly defined. This may be required, for example, when creating a model for simulation. Also, it may be necessary to define model structures that are not of black–box type, but contain more detailed internal structure, reflecting some physical insights into how the system works.

The general way of models and model structures representing in the System Identification is the using of various model objects, these will contain a number of properties.

**4.2. Arx model**

The ARX model syntax described by "Aguirre (2004)", is given in the Eq.(2). The ARX model structure, $A(q)y(t)=B(q)u(t-nk)+e(t)$ has its parameters, Eq.(3), are estimated using the least squares method. The data set is an object that contains the output and input data. The orders is given by [na nb nk] that define the orders and time delay of the ARX model specifically.

The model orders can also be defined by explicit pairs (...,'na',na,'nb',nb, 'nk',nk,...). m is returned as the least squares estimates of the parameters. For single output data this is an idpoly object, otherwise an idarx object. Models with several inputs, $A(q)y(t)=B_1(q)u_1(t-nk_1)+\cdots+B_{nu}(q)u_{nu}(t-nk_{nu})+e(t)$ are handled by allowing nb and nk to be row vectors defining the orders and delays associated with each input. Models with several inputs and several outputs are handled by allowing na, nb, and nk to contain one row for each output number.

$$\begin{aligned} m &= arx(data,orders) \\ m &= arx(data,'na',na,'nb',nb,'nk',nk) \\ m &= arx(data,orders,'\mathrm{Pr}operty1',Value1,...,'\mathrm{Property}N',ValueN) \end{aligned} \tag{2}$$

$$\begin{aligned} na &: A(q)=1+a_1q-1+\cdots+a_{na}q^{-na} \\ nb &: B(q)=b_1+b_2q-1+\cdots+a_{nb}q^{-nb+1} \end{aligned} \tag{3}$$

A multivariable ARX model with *nu* inputs and *ny* outputs given by $A(q)y(t)=B(q)u(t)+e(t)$. *A(q)* is an *ny*–by-*ny* matrix that entries are polynomials in the delay operator $q^{-1}$ represented as $A(q)=1_{ny}+A_1q^{-1}+\cdots+A_{na}q^{-na}$ as well as the matrix Eq.(4)

$$A(q)=\begin{bmatrix} a_{11}(q) & a_{12}(q) & \cdots & a_{1ny}(q) \\ a_{21} & a_{22}(q) & \cdots & a_{2ny}(q) \\ \cdots & \cdots & \cdots & \vdots \\ a_{ny1}(q) & a_{ny2}(q) & \cdots & a_{nyny}(q) \end{bmatrix} \tag{4}$$

where the $a_{kj}$ entries are polynomials in the delay operator $q^{-1}$: $a_{kj}(q)=\delta_{kj}+a_{kj}^1q^{-1}+\cdots+a_{kj}^{na_{kj}}q^{-na_{kj}}$. This polynomial describes how old values of output number *j* affect output number *k*. The $\delta_{kj}$ is the Kronecker delta; it equals 1 if $j=k$, else, it is 0. Similarly, is an *ny*–by–*nu* matrix, $B(q)=B_0+B_1q^{-1}+\cdots+B_{nb}q^{-nb}$ or **eq. (5).**

$$B(q)=\begin{bmatrix} b_{11}(q) & b_{12}(q) & \cdots & b_{1nu}(q) \\ b_{21}(q) & b_{22}(q) & \cdots & b_{2nu}(q) \\ \cdots & \cdots & \cdots & \vdots \\ b_{ny1}(q) & b_{ny2}(q) & \cdots & b_{nynu}(q) \end{bmatrix} \tag{5}$$

With. $b_{kj}(q)=\delta_{kj}+b_{kj}^1q^{-nk_{kj}}+\cdots+b_{kj}^{nb_{kj}}q^{-nb_{kj}-nk_{kj}+1}$ The delay from input number *j* to output number *k* is $nk_{kj}$. To link with the structure definition in terms of na, nb, nk in the arx and iv4 commands, note that na is a matrix whose *kj* element is $na_{kj}$ while the *kj* –elements of nb and nk are $nb_{kj}$ and $nk_{kj}$ respectively.

The idarx representation of the model can be created by m = idarx(A,B) where A and B, Eq.(6), are 3D arrays of dimensions ny-by-ny-by-(na+1) and ny-by-nu-by-(nb+1), respectively, it define the polynomial matrices Eq. (4), (5) and (6).

$$A(:,:,k+1) = A_k$$
$$B(:,:,k+1) = B_k \tag{6}$$

Note that $A(:,:,1)$ is always the identity matrix, and that leading zero coefficients in B matrices define the delays.

**5. RESULTS**

The simulations were realized with several coils and all stands, to simplify here will shown the data results of stand 5 for one coil.

The total process time is 179.96 seconds, where: 37 seconds represent acceleration time and 37 seconds are the deceleration time.

The system identification process were realized with available variable set of the Eq. (7) and Fig. 7 to 13 where the Figs. 7 to 11 show the input variables and the Figs. 12 to 13 show the output variables. Also in this figures the blue lines are unprocessing signals and red line are processed signals to system identification and green line are processed signals to validate system models.

$$(h_o, P) = f(h_i, t_b, t_f R, W) \tag{7}$$

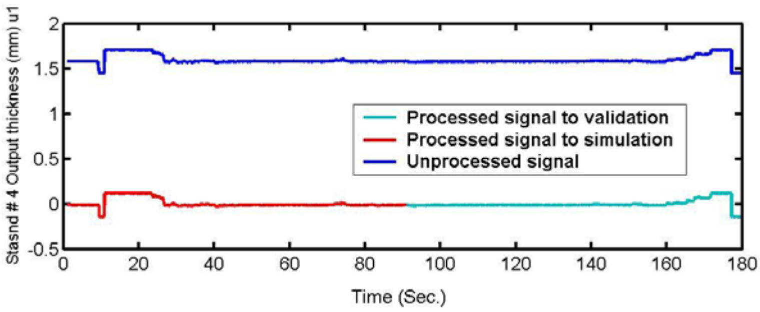


Figure 7. The input thickness of stand #5.

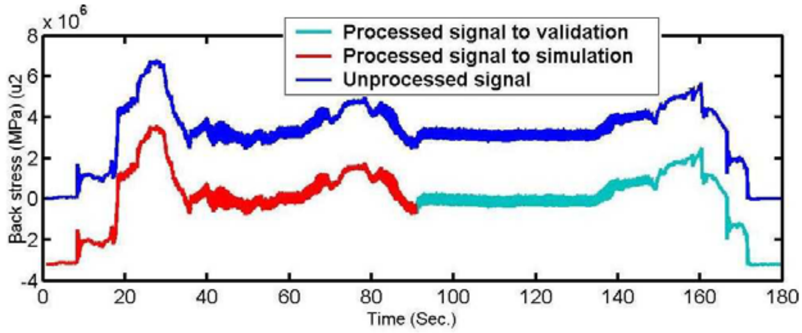


Figure 8. Back stress interstand 4 and 5.

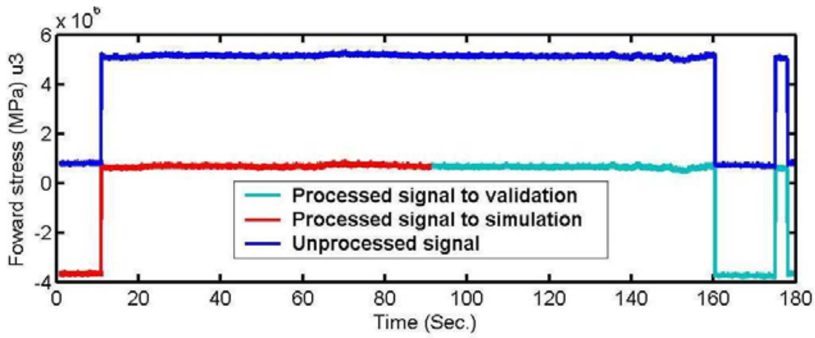


Figure 9. Forward stress of stand # 5.

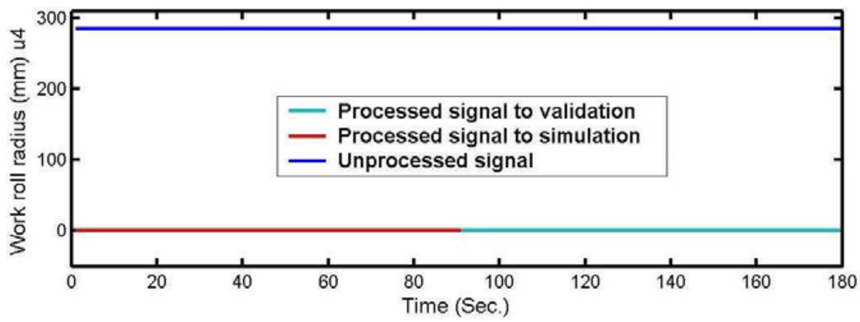


Figure 10. Work Roll Radius of stand # 5.

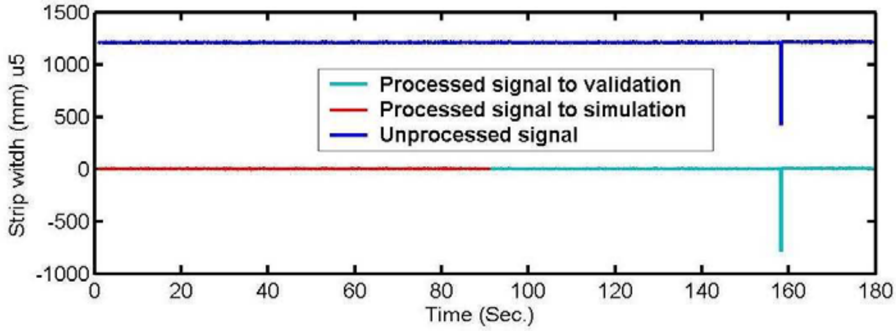


Figure 11. Strip witdh in stand # 5.

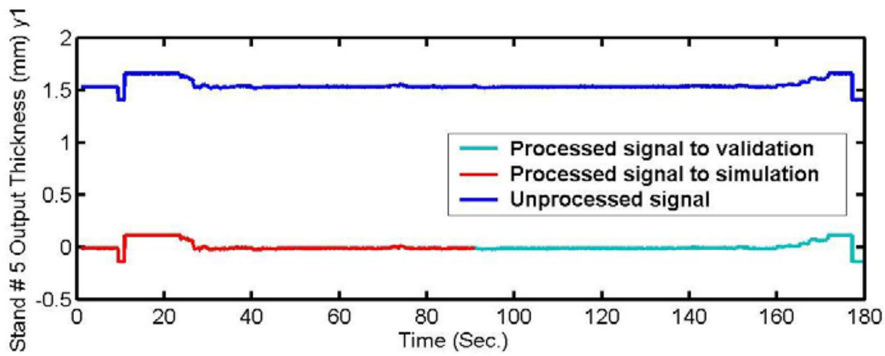


Figure 12. The output thickness of stand #5.

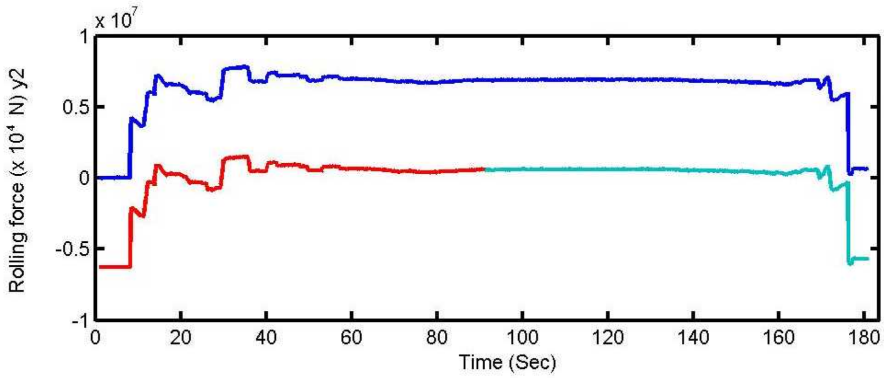


Figure 13. Rolling force of stand #5.

The results are shown in the Eqs.(8) and (9) and Figs. 14 and 15, where: black line are validation data and blue line are system identification results.

$$A_0 y(t) + A_1 y(t-T) + \cdots + A_n y(t-nT) = B_0 u(t) + B_1 u(t-T) + \cdots + B_m u(t-mT) + e(t) \quad (8)$$

The resulting system identification models is a ARX 221 Model with a fitting of 90%, where the input and output parameters orders given in the Eq.(9) is 2 and there is one delay time described by nk.

$$\begin{aligned} &ARX221 = arx(mydatade, [na, nb, nk], 'Focus', 'Sim') \\ &na = \begin{bmatrix} 2\,2 \\ 2\,2 \end{bmatrix}, \quad nb = \begin{bmatrix} 2\,2\,2\,2\,2 \\ 2\,2\,2\,2\,2 \end{bmatrix}, \quad nk = \begin{bmatrix} 1\,1\,1\,1\,1 \\ 1\,1\,1\,1\,1 \end{bmatrix} \end{aligned} \tag{9}$$

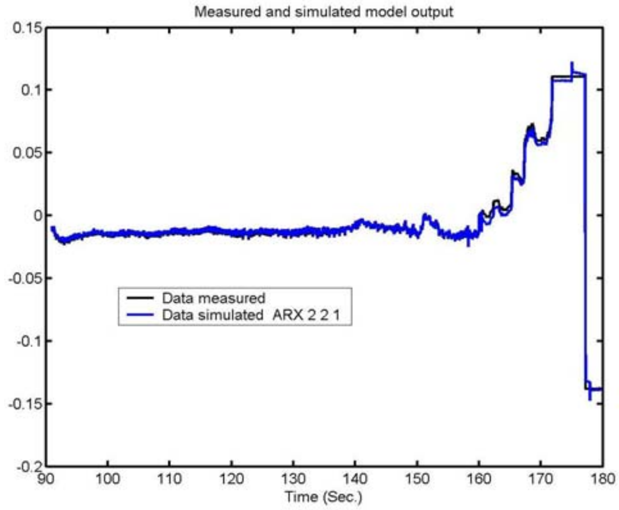


Figure 14. Strip Output thickness in stand # 5.

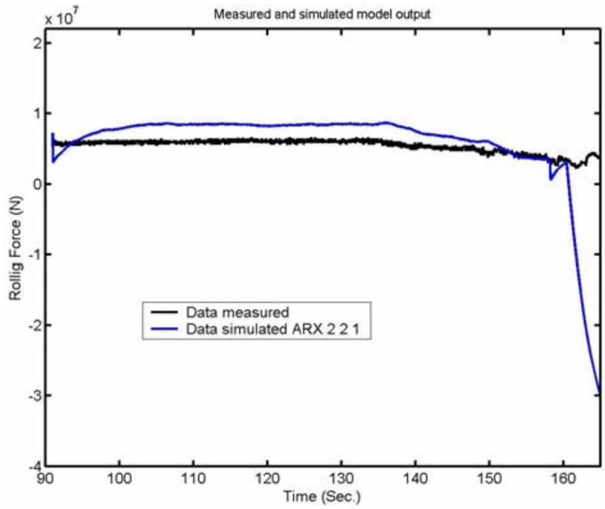


Figure 15. Rolling Force of Stand #5.

## 6. CONCLUSION AND COMMENTS

Several model structures presented in the section 4.1 were tested with measured data and the model structure which better adjustment was ARX models 2.2.1.

The identified models built in the matrix-vectorial form as section 4.2, where each term of these may be related with an input variable then these are classified as Gray-Box models.

The output thickness resulting models present adjustment of 90%, which is very good for identified models as described by Aguirre (2004). This may be explained by the existent linearity between the output and the input of model as described by Assis (Currently 2007), who studied models involve all cold rolling process to predict the output thickness and correction of its deviation.

The rolling force presented a very good adjustment between simulated results and data measured in the processing time range, but the rolling force presented a considerable deviation between simulated results and data measured in the decelerating time. This fact may be due to non- linearity among the input variables and the rolling force or the sensibility loss of control system in the decelerating time. This fact will be better investigated in Assis (2007). Still in this case, the resulting models are discrete and linears and they analyze time evolution of cold rolling process, that allows the better understanding of its behavior.

## 7. ACKNOWLEDGEMENTS

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