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Model Based Control System for Hot Steel Strip Rolling Mill Stands

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Abstract: As part of a research project on El-hadjar Hot Steel Rolling Mill Plant Annaba Algeria a new Model based control system is suggested to improve the performance of the hot strip rolling mill process. In this research off-line model based controllers and a process simulator are described .The process models are based on the laws of physics. these models can predict the future behavior and the stability of the controlled process very reliably much better than other non-model based (AI) methods. The control scheme consists of a control algorithm . This model based control system is evaluated on a simulation model that represents accurately the dynamic of the process. Finally the usefulness to the Steel Industry of the suggested method is highlighted.

Key words: Hot rolling mill train, rolling mill stands, hot steel strip, static model, dynamic model, mill stands set-up, thickness control, thickness prediction, tension control, temperature prediction, model based control, feedforward control, feedback control

INTRODUCTION

In hot steel strip rolling process both feedforward and feedback control are necessary to reduce the effects of rapid strip thickness variations due to skid marks , roll eccentricity and other factors such as supports deformation, bearings as well as long term or slow variations of thickness in the six stands finishing train. Dairiki *et al*., 1989; Ford and Alexander, 1963; Min *et al*., 2004; Pederson, 1999; Gomez, 1980; Eustace, 1963; Misaka *et al*., 1967; Robert, 1983; Walter *et al*., 2001; Pittner and Marwan, 2006; Siegfried *et al*., 2004.

The consideration of model based control in hot steel strip rolling mill in which there is thickness, Tension and temperature control, involves the resolution of many problems.

The main problem is that both good static and dynamic mathematical models must be found so that this allows the investigation and observation of many phenomena and parameters than we could measure in a real situation in the Steel Rolling mill plant. This of course permits the synthesis of good feedforward or feedback controllers.

Process description: In a hot strip rolling mill, finishing mill train is a kind of process that makes strips from thick slabs which have been produced by continuous casting. A typical process shown in Fig. 1 consists of rolling stands where the attached rolls are used to press the steel slab. After a slab is reheated to re crystallization temperature in the furnace, it is reduced in several passes in a roughing mill before being rolled in the finishing hot rolling mill train.

Hot strip thickness control system: As shown in Fig. 2 the hot strip thickness control system called also Automatic Gage Control (AGC), is intended to maintain the thickness (the gage) of the strip constant at a predetermined value. To satisfy this condition, finishing train stands must feature roll positioning systems (hydraulic screw drives) capable of High speed operational response under full rolling load and should be equipped with load cells for the measurement of rolling force and a position measuring device (Wada *et al*., 1994). Because of the pure time delay involved when making the measurement of the thickness down the rolling line this leads to the necessity of using a mathematical model of the system to be controlled and as it is well known the Smith predictor is often used in these sorts of situations. The classical Smith Predictor (Walter *et al*., 2001) certainly improves the response of the overall system but does not combat disturbances. The method that avoids the effects of the pure time delay introduced by the thickness measuring device and gets the Stand exit thickness from the force on the Stand Work Rolls is known as BISRA (Eustace, 1963; Misaka *et al*., 1967; Robort, 1983). Control Method. In what follows we will improve the Smith

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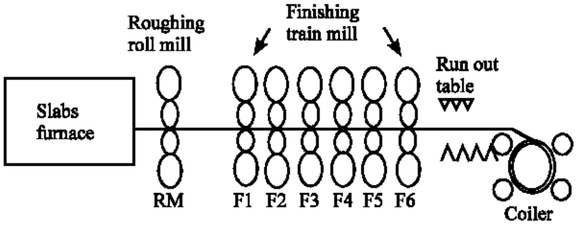

Fig.1: Hot steel strip rolling mill train

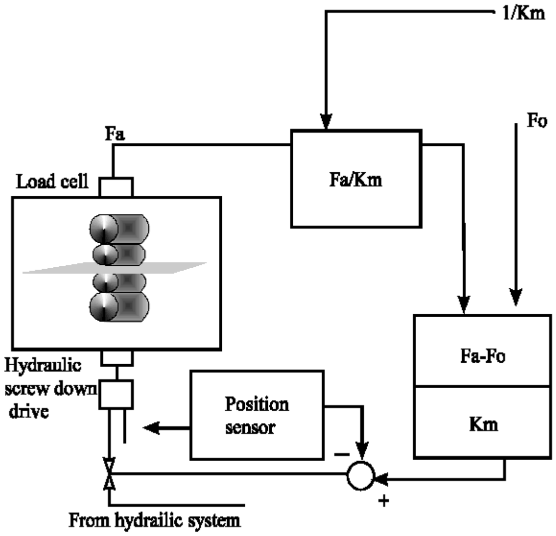

Fig 2: Hot strip thickness basic (BISRA) (Eustace, 1963; Misaka *et al.*, 1967; Robort, 1983) control system

Predictor control system and the BISRA Gages by usingevolved mathematical Models derived from the industrial process nature using basic laws of physics.

MATERIALS AND METHODS

Static roll gap model solution for rolling mill set-up prediction: The fundamental Orowan's differential equation for a rolled strip (Robert, 1983) is:

$$\frac{dF_H}{d\beta} = 2R * P\left(SIN\beta \pm uCOS\beta\right) \qquad (1)$$

Where:

F_H = Horizontal Force applied to a strip unit section.
β = Angle of no slip point
R = Roll radius
P = Pressure applied to a strip unit section.
u = Friction coefficient

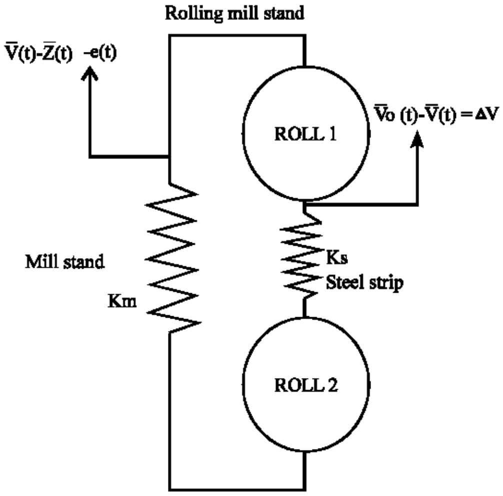

Fig. 3: Steel Strip and Mill stand modeled (Pederson, 1999) as two springs with constants Km and Ks. v (t), z (t) and e (t) are thickness, roll position and eccentricity variables (ΔV) is the thickness deviation , Vo (t) is the incoming thickness, V (t) is the outgoing thickness

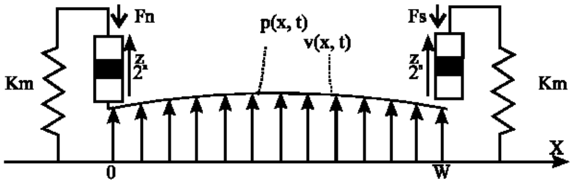

Fig. 4: Top half rolling mill stand physical model (Pederson, 1999) with mill stand spring constant (modulus) km. Fn (t) and fs (t) are drive side and operator side forces. V (x, t), z (t) , p (x, t) and w (0, w) are, respectively steel strip thickness profile, roll position, pressure distribution between steel strip and roll, w (0, w) is the strip width

The solution of the above differential Eq. (1) by many authors: Sims, Bland, Ford, Siebel, Ellis……. With different physical hypotheses and approximations led to the prediction of the results below: Predictions of force , thickness, temperature, torque, powers, forward slip, strip entry and exit speeds and rolling pressure:

$$V(t) = Vo + 2R'(1+\cos\beta) \qquad (2)$$

thickness at any point and Time predicted by (2) in the roll Gap.
R'= the deformed work roll Radius
(Hitchcock's formula see below (9)

From (Dairiki *et al.*, 1989; Ford and Alexander, 1963-64; Min *et al.*, 2004; Pederson, 1999; Gomez, 1980; Eustace, 1963; Misaka *et al.*, 1967; Rebert, 1983; Walter *et al.*, 2001; Pittner and Marwan, 2006; Siegfried *et al.*, 2004) and the schematic representation given in (Fig. 2-4) when ignoring the chatter e (t) due to eccentricity of the rolls and other less important factors (oil film ,thermal camber etc …) the desired finishing thickness Vd (3) and the attained thickness V are expressed by

$$Vd = Zo + (Fo / Km) \tag{3}$$

$$V - (Fa / Km) - \Delta Z = Zo \tag{4}$$

$$V = Zo + (Fa / Km) + \Delta Z \tag{5}$$

Where: Zo: Unloaded roll gap (Set-up Roll Gap), Vo incoming thickness, V is the Outgoing thickness (5) (output or actual thickness) F0: Reference roll force, Fa: Actual rolling force, Km: Mill Spring Constant (Mill Modulus), ΔZ: Change in roll gap by AGC (Correction based on X-Rays thickness meter). The thickness deviation is then:

$$\Delta V = Vo - V = ((Fa - Fo)/ Km) + \Delta Z \tag{6}$$

As in the ideal case ΔV must tend to zero So that The thickness would reach the desired value. The basic control equation is:

$$\Delta Z = - (Fa - Fo) / Km \tag{7}$$

For a measured or predicted material temperature of a given steel grade and calculated rolling speed, the actual rolling force is calculated by
Sims/Orowan efficient formula (Ford and Alexander, 1963; Min *et al.*, 2004; Pederson, 1999; Gomez, 1980):

$$Fa = 1.15.b.k1.Qp\sqrt{R'i(Vo - V)} \tag{8}$$

A = L (bite contact length)/V
R'i = Hitchcock's Roll Radius equation (Eustace, 1963)

$$R'i = Ri[1 + Ci\frac{Fa}{\Delta V}] \tag{9}$$

R' is the loaded stand work roll radius.
Ri = Unloaded work roll radius
Ci = Constant depending on roll's material elasticity
Usually between 0.00021mm^2/N and 0.00025mm^2/N for hard steel rolls.
Where also:

T: Strip temperature, k1: deformation resistance, b: Strip width, Ri': Loaded Work roll radius, Vo: Input thickness, V: output thickness .
k1 [kgf/mm^2]= K2*K3 is calculated by the use of Misaka's *et al.* (1967) deformation resistance prediction equation:

$$K2 = \exp[0.126 - 1.75c^2 + (\frac{2851 + 2968c - 1120c^2}{T})]$$
$$K3 = \varepsilon^{0.21}[\frac{d\varepsilon}{dt}]^{0.13} \tag{10}$$

c: Slab Steel carbon content [weight %] T: Rolled Steel Absolute Temperature [K] ε True Strain of deformation in mm per unit length
$\frac{d\varepsilon}{dt}$ Strain Rate of deformation (1/s)
t : Time (s) The Mean Strain Rate is:

$$\text{Mean } \frac{d\varepsilon}{dt} = \frac{Vroll \ln\left(\frac{V}{Vo}\right)}{R'\sqrt{V - Vo}} \tag{11}$$

Usually taken as 10^{-2}-200(1/s)
For Mild steel , high carbon and low-alloy steel.

The steel strip temperature is predicted by: Knowing the temperatures of the strip measured by Pyrometer at the entry point of stand F1 and at the exit point of the last stand F6 , the temperature of the strip at each stand could be predicted by (12) :

$$T_i = T_{(i-1)} - \Delta T_i(irr) - \Delta T_i(desc) - \Delta T_i(csr)$$
$$+\Delta T_i(defo)...(12) \tag{12}$$

Tirr = irradiation temperature Drop; Tdesc = descaling temperature Drop; Tcsr = contact strip/roll temperature Drop, Tdefo = deformation temperature gain.
$\Delta T_i(defo) = k1\varepsilon / \rho C_P$ = Temperature Gain (13)

Cp = Steel heat capacity
k1 = Deformation resistance as above
ε = True Strain of deformation
ρ = Steel's density

All Temperatures could be calculated by a temperature model calibrated to the considered rolling mill train by (14) Formula:

$$T_i = T_w - (T_{i-1} - T_w)\exp\left(\frac{-2\alpha_F L_1}{C\rho V_F V_{ST}}\right) \tag{14}$$

T_W = Cooling Water Temperature

L_I = Distance between Stands
V_{ST} = Strip threading speed (meters/h)
V_F = Finishing Mill delivery thickness in meters.
α_F = constant
C ' = Specific Heat (kcal/kg °C degrees centigrade)
ρ = Density (kg/square meter)

The total rolling Torque is predicted by (15):

$$TRM = (2*Fa*La)/1000 \qquad (15)$$

La = (C1*C2*exp(C3*D/2*V)*L' = The lever arm where L' is the contact bite length , D is roll diameter C1,C2,C3 are known constants.

Torque at the motor shaft (16):

$$TMSH = TRM/\text{gear ratio (gr)}*\text{efficiency}(\eta) \qquad (16)$$

The electrical input power(17) :

$$KW = TRM*Wroll(rd/s)/\eta = TRM *Vroll\ (rpm)*1000/R\ \eta \qquad (17)$$

Forward slip ratio model (18):

$$fos = (Vstrip - Vroll) / Vroll \qquad (18)$$

The Slip model allows the prediction of the strip input and output speeds of any stand starting from the roll speed of the considered stand.

The Angle ß of no Slip point see Fig. 5 can be calculated (Robert, 1983) by (19):

ßeta =β =

$$= \frac{\sqrt{V}}{\sqrt{R'}} \tan\left[\frac{\Pi}{8}\left(\frac{\sqrt{V}}{\sqrt{R'}}\right)\ln(1-r) + \frac{1}{2}\tan^{-1}\left(\frac{\sqrt{r}}{\sqrt{r-1}}\right)\right] \qquad (19)$$

Thickness Reduction r = Vo – V

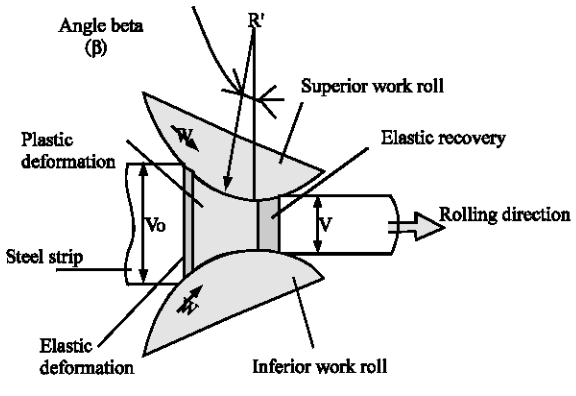

Fig. 5: Schematic diagram of material deformation. At a rolling stand

Vexi = exit speed from stand Fi is predicted by (20)

$$Vexi = V_{roll}\left[1 + \left(\frac{2R'}{V}COS\beta - 1\right)(1 - \cos\beta)\right] \qquad (20)$$

Elongation of the strip: The elongation EL must be kept constant in order to get a Constant strip tension between stand Fi and F I+1 Or Fi-1:

$$EL = (Vexi - Vientry) / Vientry \qquad (21)$$

Rolling Speed at Stand Fi :

$$Vrsi = (1+ fos6)V6*Vrs6) / (1+ fosi)Vi \qquad (22)$$

The last F6 stand rolling speed Vrs6 is directly introduced by the operator at the start of every rolling campaign.

The Rolling pressure (Ekelund Formula) (23):

$$Ps = (Ka*\ n*u)*(1+m) \qquad (23)$$

Where : Ka = (14-0.01t)(104+C+Mn+0.3Cr)
n = 0.01(14-0.01t)Cv

$$u = \frac{2000J\sqrt{2\Delta V/d}}{Zo + Vo}$$

Zo = Set-up gap
ΔV = Thickness deviation (6)
J = 0.5(Vrollsup-Vrollinf)
u = Friction coefficient = 1.05-0.0005t
d = Work roll diameter
CV = $1.0942.e^{-0.03J}$

RESULTS AND DISCUSSION

The calculation of the Set-up Fig. 6 is in reality executed on-line in the real time available after the slab leaves the roughing mill and before it enters the first stand of the finishing train which has the main specifications shown in Table 1.

Table 1 EL- Hadjar (1979): Hot steel rolling mill finishing train Annaba, Algeria , plant specifications

Finishing mill type	6 stands equippedwithhydraulic screw-downs
Nominal power	2×3000 HP, DC
Rolling thickness range	1.5 to 15 mm
Strip width range	600 to 1350 mm
AGC (Autom. Gage Control)	Hydraulic
Gauge meter	X Ray
Rolling speed	49 to 407 rpm
Mean mill stretch	1000 tons/mm
Rolling temperature	860 to 880°C
Production capacity	1. 5 Million tons per year

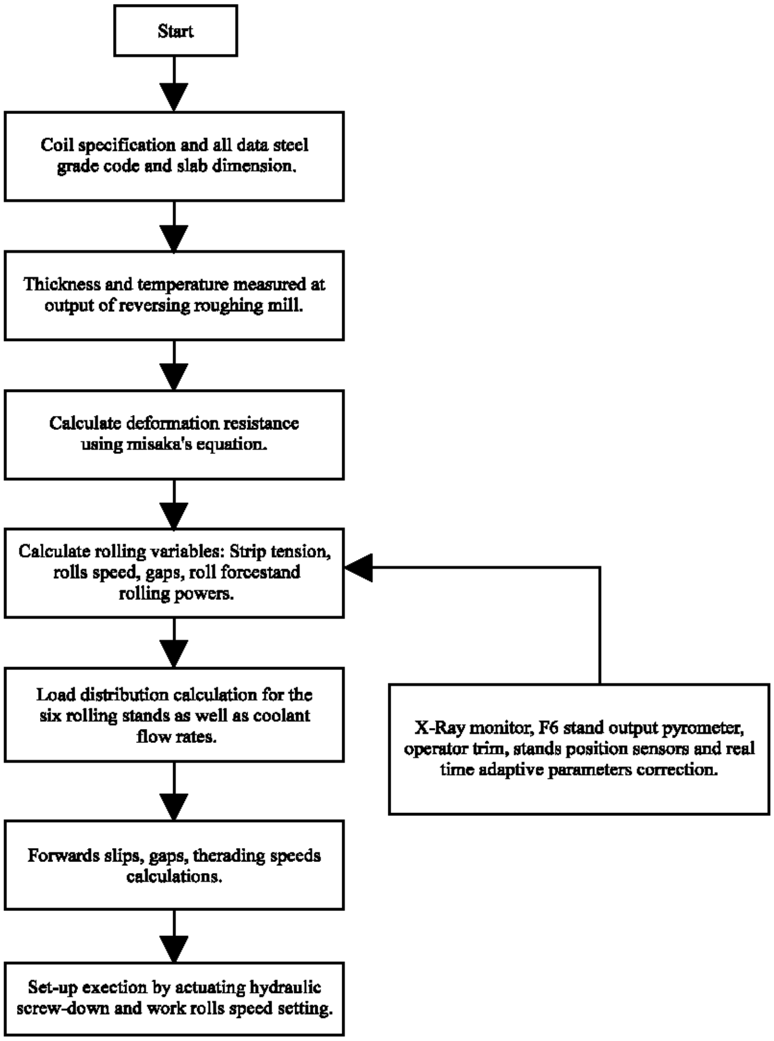

Fig. 6: Simplified hot rooling mill finshing train simulator flow chart

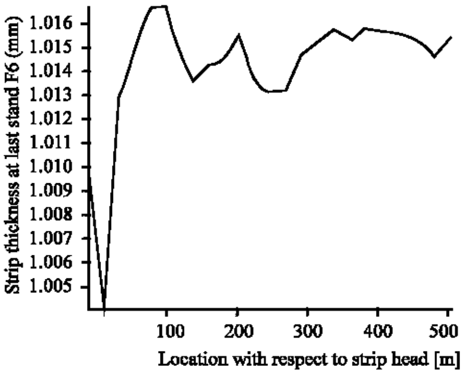

Fig. 7: Evolution of calculated stand F6 exit thickness

In order to verify that the Simulator satisfies the time constraints and gives good prediction of Rolling Variables, off-line Simulations using real process data is introduced into the Simulator program.

To keep the thickness deviation Fig. 7 to the specified minimum dictated by the client the simulator developed makes two sorts of adaptations one is between Stand (I) and Stand (I+1) in the Feed forward control Mode Fig. 8 and the second adaptation is done in the Feed back Mode Fig. 9 and 10 or something that could be called (Learning Mode) using data from the X.Ray Monitor and Pyrometer Fig. 6 of one coil and correcting the Rolling variables in the next run during the Rolling of the next Slab. If we look at Fig. 6 the words (Operator Trims) are still in the control system, this is because there is always a restricted precision of the process Model but nevertheless the accuracy is getting better every day and the operators are needed less and less than before in modern rolling mill plants.

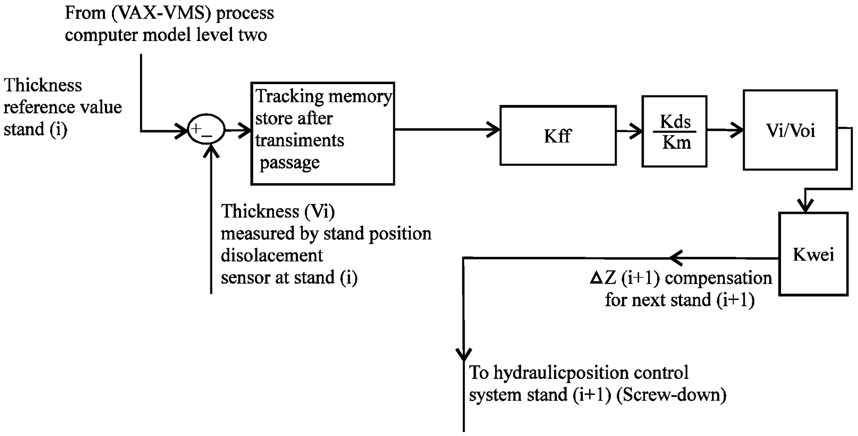

Fig. 8: Simplified block diagram of the feedforward thickness control AGC. (Automatic Gage Control) Kff = feedforward gain, Km = Stand Spring constant; Kds = Steel Strip deformation constant; Voi = incoming thickness at stand (i) Vi = outgoing thickness at stand (I) (as defined before); Kwei = weighing factor of stand (I); ΔZ (I+1) = additional roll gap correction for next stand (i+1)

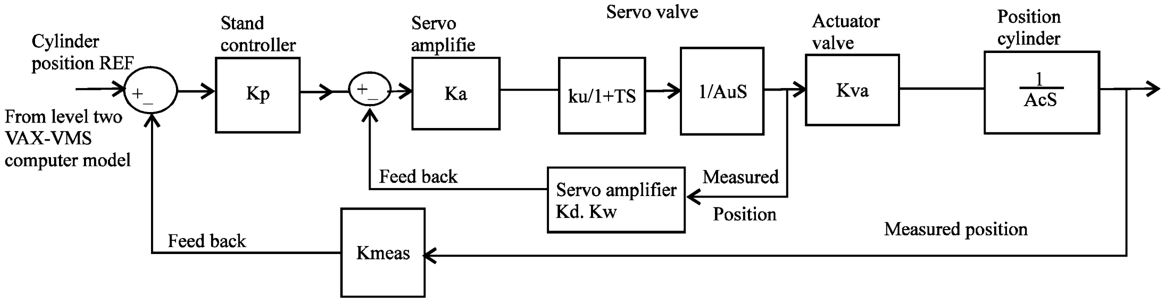

Fig. 9: Simplified bolck duagram of hair stand position control system with componsation dynamic models. As in Fig. 7 the stands position feedback control system is composed of two closed loops: One called the operator or south side loop the other called the drive or north side loop

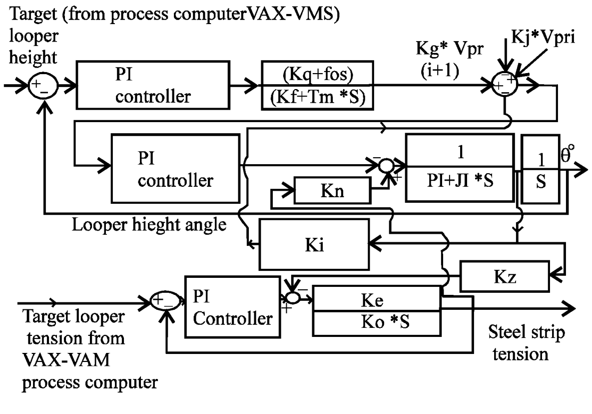

Fig. 10: Simplified looper control and its dynamic model block diagram.Vpri and Vpr(n+1) are Work rolls peripheral speeds; Tm identified Motor Time constant Jl = Looper Inertia; Pl = Looper damping constant; fos = Forward Slip

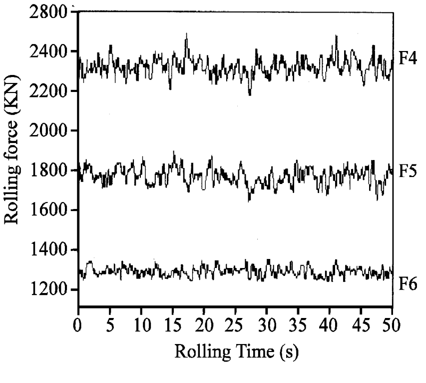

Fig. 11: Evolution of calculated stands roll Forces

different rolling forces applied to stands F4, F5, F6, (Fig. 12 and 13) represent the simulated results for the speed and torque at stand 3. These simulated results are more or less the same as the practically measured by

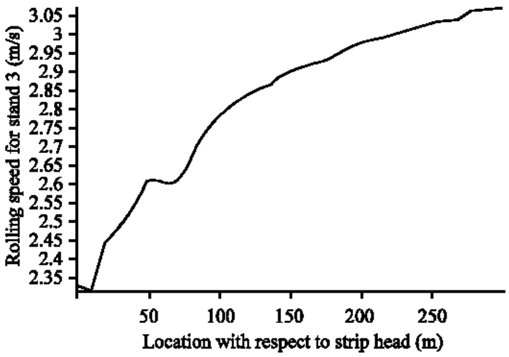

Fig. 12: Evolution of calculated stand 3 rolling speed

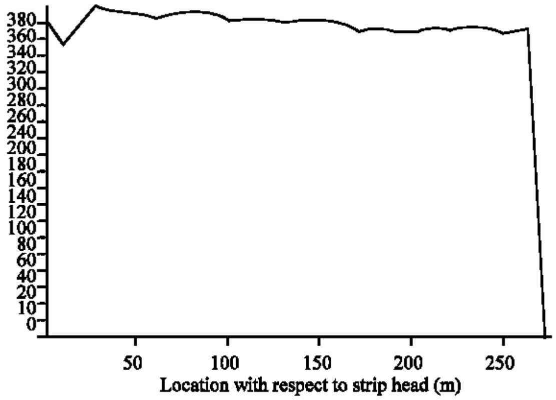

Fig. 13: Evolution of calculated torque at stand 3

(force, speed and torque) captors in a practical rolling mill of the same size as the El-Hadjar finishing rolling mill simulated in this project.

CONCLUSION

An off-line hot steel strip rolling mill simulator was elaborated and tested under mainly Fortran language because of the types of calculations involved on the level two mainframe (Vax) process computer (formulae type) using off-line plant Data from the El-Hadjar Annaba Algeria six Stands finishing train. From the simulation results Fig. 7, 11-13, the usefulness and effectiveness of the suggested System and models were proved. Moreover, it is well shown that mathematical model based control of industrial plants is more reliable than non model (AI) based control because of their real physical modeling and their predictable stability and behavior. The new Simulator presented has good performance in terms of computing time and accuracy. The results obtained up to now are quite promising for future implementation practically on-line in the industrial finishing train.

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