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# DYNAMIC SIMULATION OF ROLLING ON A SIX STAND HOT STRIP MILL

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## INTRODUCTION

Competition from Far Eastern and other European steel makers along with a shift in demand towards higher quality steel strip demands continual improvement in quality of the finished product of hot strip rolling mills. Until recently this demand has been met by improving 'off-line' models for calculating control setpoints, replacing outdated computer and control hardware and by optimising adaption algorithms. Relatively less effort has been spent on the dynamic control of these mills, which typically consist of multiple 'single loop' controllers. Due to the complexity of the hot strip rolling process, simulation is indispensable in the understanding of its control systems. This paper describes the development of dynamic simulations of the finishing train of Lackenby Coil Plate Mill (British Steel Ltd now part of the Corus Group) for the purpose of investigating advanced control strategies.

Comprehensive dynamic models of the mill mechanical, electrical and control systems combined with models of the hot strip characteristics allowed the creation of complete simulations of the mill. Results from the simulations are analysed by graphical comparison with actual plant measurements. Real time animations allowed visualisation of complex dynamics such as the behaviour of strip in the interstand region.

## THE HOT STRIP ROLLING MILL

Upstream of the finishing train, steel slabs are reheated to around 1250$^o$C and rolled in a series of passes in a roughing mill to become a plate of around 30mm thick and 40m long with a temperature now reduced to 1050$^o$C. The finishing train of the Coil Plate Mill consists of six rolling stands, operating in tandem, that reduce the plate to the desired final thickness. Loopers installed between the rolling stands allow for speed differences between stands and enable control of interstand strip tension during rolling. Figure 1 shows the arrangement of two stands and one looper.

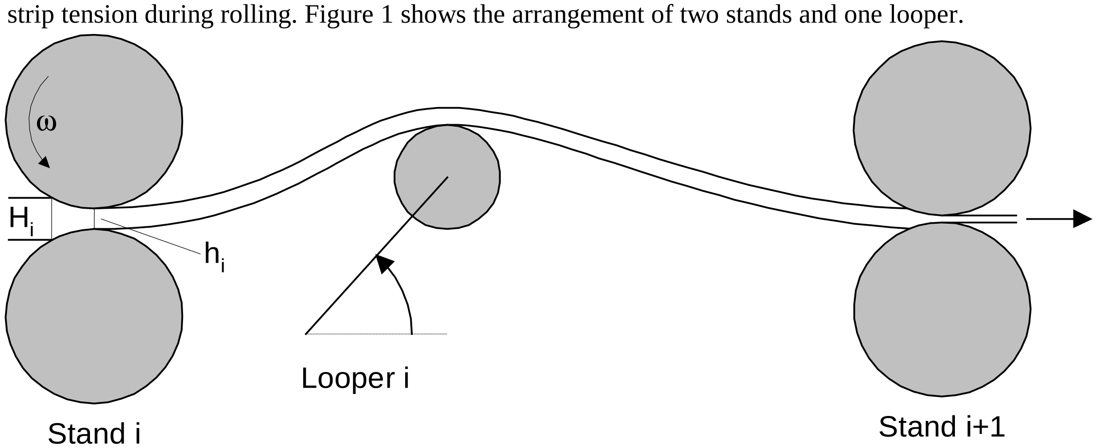


**Figure 1. Two stands and one looper**

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The final strip quality is characterised by

- product geometry
- mechanical properties

Product geometry includes the gauge, crown, flatness and width of the strip. The height and profile of the roll gap set the gauge and crown of the strip. Flatness discrepancies occur when the input profile of the strip departs from the roll gap profile, resulting in varying elongation over the strip width causing internal strip tensions. If internal strip tensions are within buckling limits the strip appears flat. The coil plate mill has no explicit means of varying roll gap profile (such as work roll bending found on other mills) so profile and flatness are only influenced by how the rolling forces are distributed between the finishing stands.

Edging rolls in the upstream roughing stand control strip width. Width is not directly controlled in the finishing mill however excessive interstand tensions can lead to unwanted changes in width due to necking.
The steel composition, the amount of deformation and the cooling path to the target coiling temperature determine the strip mechanical properties. After rolling the strip is cooled down on a run out table and coiled at the down-coiler.

**Mill control**
The mill is controlled in three main stages during threading a coil through the mill, coupled rolling and de-threading the mill. Dynamic control during coupled rolling entails regulating the:

- Exit gauge ($h_i$) of each stand
- Strip tension between stands
- Strip temperature at the finishing mill exit

Strip tension and stand exit gauges can not be measured so are estimated by on-line models. The roll gap and hence exit gauge of each stand is set by electric screwjacks that set the unloaded roll gap. The actual gap depends on the rolling load due to stretch of the mill stand housing that must be taken into account in the unloaded gap settings. Automatic gauge control (AGC) dynamically adjusts the roll gaps, to account for variations in load during rolling, according to a model of stand stretch characteristics. An X-ray gauge at the exit of the mill measures the final gauge and feeds back errors to all rolling stands through the X-ray gauge control mechanism.

Hot strip experiences a longitudinal tension due to the looper force acting vertically on the strip. This tension stress appears at the exit of the upstream and entry of the downstream roll gaps, affecting the forces appearing in those roll gaps. The loopers are position controlled until they contact the strip after which they are torque controlled to maintain a reference strip tension, according to a 'straight line' tension model. Looper movements accommodate variations in mass flow between stands. Varying the upstream stand speed reference according to looper angle controls the loop height. Adjusting the overall rolling speed controls the strip temperature at the exit of the finishing mill.

## SIMULATION DETAILS
The SIMULINK software package provided the environment for constructing simulations as hierarchical block diagrams made up from the following sub-models. Although many elements of the finishing mill were represented using standard SIMULINK blocks, certain aspects had to be implemented as S-functions, coded in C for speed.

**Interstand and Roll Gap models**
The roll gap model describes the behaviour of the hot strip during deformation in each of the roll gaps. Rolling forces and torque models are based on Sim's solutions for the roll gap. The geometry of the roll gaps and the tension stress at their entries and exits determine the boundary conditions for these models. In coupled rolling the tension stresses are significant and must be solved from a consideration of interstand strip mechanics.
The interstand model based upon the concept of the strip as a moving elastic beam, uses standard momentum and small angle beam theories. After some simplification the motion of this elastic beam can be described by a fourth order partial differential equation of the following form:

$$\frac{\partial s}{\partial t}+2u\frac{\partial s}{\partial y}+s\frac{c}{\lambda}=p\frac{\partial^2 y}{\partial x^2}-\frac{\upsilon}{\lambda}\frac{\partial^4 y}{\partial x^4}-g+\frac{10}{\lambda}\frac{F_y}{\partial x}$$

with known quantities:

$\lambda$ = mass per unit length of beam in the interstand region
$\upsilon$ = section modulus of beam
c = damping term for vertical velocity
g = gravitational force
$F_y$ = vertical force applied by looper torque motor at a point along the strip
t = time in seconds
x = distance along the strip from upstream end

and unknowns:

y = height of strip above datum (zero at boundaries)
s = $\partial y/\partial t$ vertical speed of strip (zero at boundaries)
u = horizontal speed of strip in the interstand region
p = dummy variable ('pressure') defined by the relationship:

$p=\left(\frac{\sigma}{\lambda}-u^2\right)$ where $\sigma$= normal stress along the beam

The equation is solved numerically using a method more commonly found in computational fluid dynamics, the dominant feature of which is the imposition of mass conservation through the solution of a pressure correction algorithm (hence the term 'p' above). The new solution method is very robust allowing coarse space and time division. Previous solution attempts, including finite elements and other finite difference solvers, all proved too slow or unstable. Dr Alan Bush (previously reader in maths at Teesside University) proposed and devised the new solution method.

*Coupling between roll gap equations, looper dynamics and the interstand model*
The above 4th order pde describing the motion of strip in the interstand region is coupled at the inlet and outlet boundaries to the solution of the roll gap equations. The mass flow rate through each stand is a function not only of stand speed but also the reduction ($h_i/H_i$) taking place at that stand. Using perturbation theory, Sim's solution for the roll gap can be linearised to give the strip velocity at the exit of the roll gap as:

$$u_{out} = a + b(\sigma_f - \sigma_b)$$

Where terms a and b are solved at each time step from roll speed, gap geometry and material flow stress. Front and back tension stresses $\sigma_f$ and $\sigma_b$ appear as boundary terms in the previous 'p' equation.

When the looper roll contacts the strip, the looper roll mass joins the strip so the looper equation of motion must also be solved with the strip equation in a coupled form. A complete coupled solution for the strip behaviour in the roll gaps, the looper equations of motion and the strip behaviour in the interstand regions was developed and coded in 'C' as a single SIMULINK S-function.

**Mill Control Hardware**
The finishing mill uses four levels of control.

- Set-up computer
- Control computer
- PLC (MultiGem)
- Drive control (GemDrive)

*Set-up computer*
A large number of 'off-line' models predict the initial set-up of the mill to achieve head end strip properties. The set-up computer determines the mill configuration and generates the initial setpoints for lower control levels. The simulation must also be configured for a particular rolling (i.e. correct start/finishing stand) and control setpoints generated in a similar way. Data from the actual set-up computer was read into MATLAB where 'off-line' routines, written as MATLAB M-functions, generated the configuration information and control setpoints for a particular rolled coil.

*Control computer*
The control computer dynamically adjusts errors in initial setpoints and maintains strip properties throughout the entire strip length. Predictive feedforward control is used to improve the gauge response of downstream stands. Functions operating in the mill control computer, written in 'C', were replicated in the simulation using plant code. S-functions were written to interface the actual control computer code with the rest of the simulation.

*MultiGems*
The Set-up computer and Control computer both communicate with the mill via PLC's (MultiGem). The Multigems also contain some control logic. Automatic gauge control (AGC), loop height control, main drive speed referencing and temperature control are all carried out at this level. The MultiGems are programmed in Gem80 relay ladder logic diagrams. All internal Gem80 calculations are carried out in integer arithmetic. The use of 'C' coded S-functions allowed exact replication of the integer arithmetic and sample rates of these systems in the simulation.

*GemDrives*
Each stand main drive has a GEM micro drive controlling the stand speed and current, with control logic to protect the motors. GEM micro drives controlling the looper motors also include the strip tension control loops. Actual GemDrive code was not available, so control functions were simulated according to drive documentation. The use of 'C' coded S-functions allowed simulation of drive sequencing and other control filtering functions, with the correct sampling rates.

**Mill Hardware**
*Main Drives*
Each stand has a 6000-hp dc motor driven by a half suppressed thyristor bridge controlled by a 'Gemdrive' microprocessor drive control unit. The drives incorporate 'spillover' field control to allow speeds above base speed.

*Looper Drives*
Loopers one and two are driven by twin 75hp dc torque motors whereas single 75hp dc motors drive the other loopers. All of the looper motors operate through 10:1 reduction gearboxes with fully controlled thyristor bridges each controlled by 'Gemdrive' units.

Main drive and looper drive mechanics were modelled as single inertia systems with modelling effort directed towards matching simulated response characteristics to plant measurements.

*Stand Mechanics*

Rolling mill stands always seem to possess non-linear rolling force vs. roll gap curves. It is important to model these curves accurately. Fitting exponential functions to mill data using least squares achieved accurate spring models. Stand dynamics are modelled as lumped parameter mass-spring-damper systems using standard SIMULINK blocks.

*Screwjack Systems*

Each stand screw jack system consists of fully controlled dc motor drives working through 500:1 reduction gearboxes. These are low efficiency drives with sticking friction. Speed and rate of current rise limits make gap responses amplitude dependent. The control bandwidth changes from about 10 rads/sec for 50 microns movements to about 1 rads/sec for 1mm. Screwjack systems are modelled partly as S-functions and partly with standard Simulink blocks.

**Input Data**

In order to run, the simulation requires data to describe the characteristics of the ingoing plate being rolled. Actual logged plant engineering data from upstream rolling processes were used to calculate the in-going strip characteristics of temperature, gauge and width along the plate length using interactive MATLAB M-functions.

## RESULTS FROM THE SIMULATION

The complete simulation represents our current best understanding of the hot strip rolling process and its dynamic interaction with the mechanical, electrical and control systems of the finishing mill. The aim of the simulation is to replicate as closely as possible the complete rolling process through the finishing mill. Achieving this aim allows the same coil to be 'rolled again' under different control strategies. A crucial aspect of the simulation is its verification.

**Simulation verification**

Not all process variables are measured or can be measured. For example, pyrometers measure the steel surface temperature at the entry and exit of the finishing mill, whereas the simulation requires the internal temperature distribution through the thickness and through the mill to determine the deformation resistance in each roll gap.
Roll diameters change with time due to thermal expansion and wear, neither of which is known with much accuracy during a rolling campaign.

Unknown variables have to be estimated from upstream process data or determined by tuning unmeasured parameters in the simulation to match logged results from actual rolling. As a consequence there is a great overlap between 'tuning' model parameters and 'verification', both being performed against actual plant logged results. Much of the simulation development has been driven by the deficiencies identified during verification.

In general mean values of process variables such as rolling loads are achieved with very little effort in terms of tuning model parameters. Replicating the transient behaviour is far more difficult; the dynamic response is highly interactive making the mill appear extremely sensitive to small changes in control actions. This is the reason the control systems have been simulated in such detail taking into account integer arithmetic, sampling effects and control limits.

**Visualisation**

Considerable use has been made of the analysis and visualisation tools of MATLAB to tune and verify the simulation against plant results. Figure 2 compares simulated mill stand loads (dashed) with loads logged during actual rolling of the coil in the mill (solid lines). The mean loads match adequately but the transient behaviour deviates particularly in the later rolling stands due to the accumulative effect of small divergences upstream.

The six stands of the finishing mill are highly interactive due to their coupling through the interstand regions. The coupled interstand, rollgap, looper model used in the simulation shows that changes in conditions in any stand directly effects the strip tensions in all interstand regions and consequently the behaviour in the rollgaps. This interaction in particular effects the loop height control system which attempts to maintain strip tension and mass flow through the mill. In such a case where process variables are highly interactive it is difficult to conceive what is happening from several plots, such as in Figure 2, using animation a much clearer picture of process behaviour can be gained. Figure 3 shows a snapshot of an animation of the interstand strip/ looper behaviour for six stand rolling.

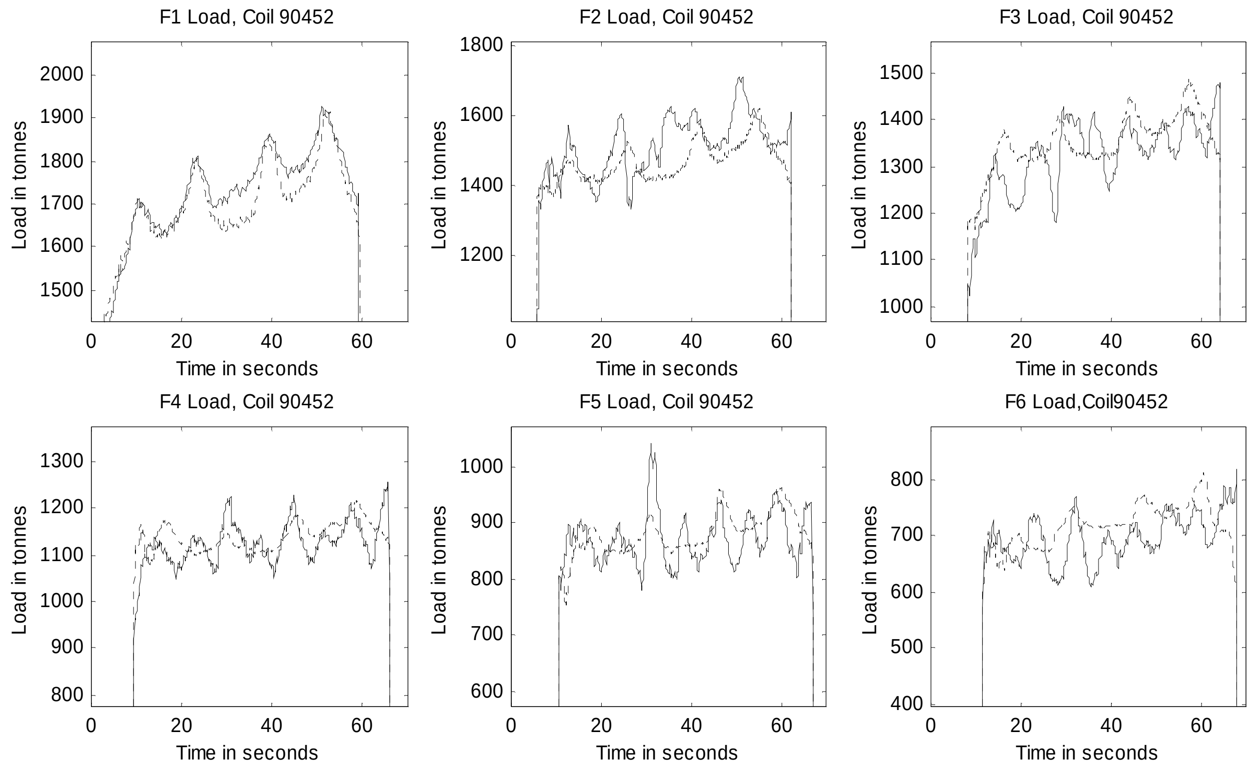


**Figure 2 Mill stand loads**

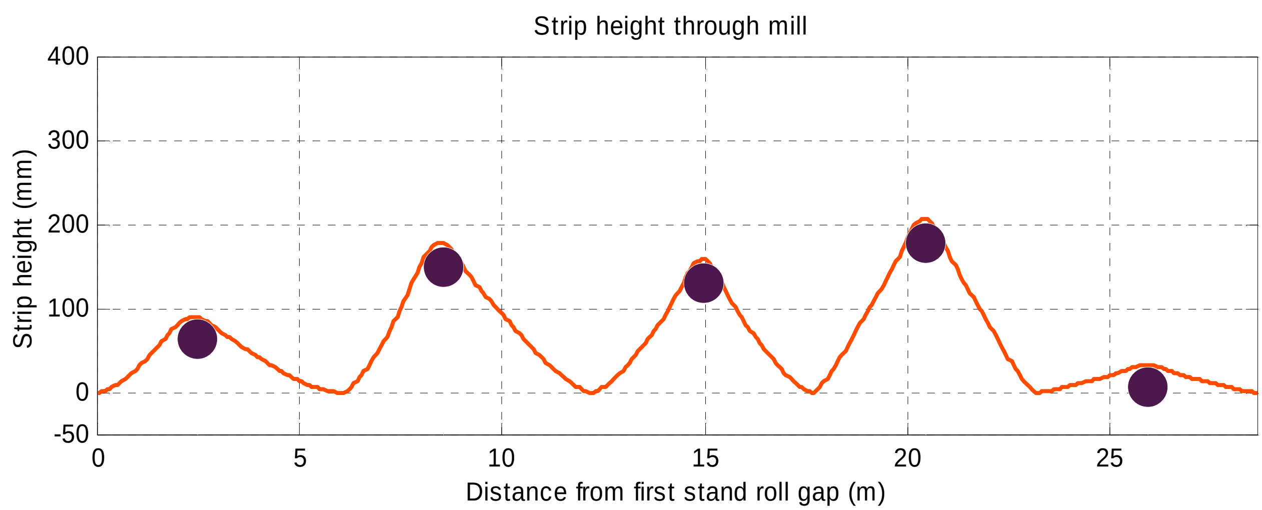


**Figure 3 Snapshot of interstand strip/looper animation**

The simulation acts as a core element for the design of control improvements. Control strategies are designed using simplified/linearised models derived from the full simulation. Developed control algorithms are tested and tuned on the full simulation. Methods investigated include the tuning of existing control loops by parameter optimisation and the application of model predictive control. The simulation highlights areas of weakness in the 'off-line' set-up models and 'on-line' control models. The simulation is under continual development; further model changes, to gain a better correspondence between real world and simulated results, are possible - the main one being a change from Sims's roll gap equation to Orowan's solution.

## FURTHER DEVELOPMENTS

Control system changes must be rigorously tested off-line to ensure that the mill is not at risk and that product quality does not suffer. The MATLAB Real Time Workshop allows us to compile the simulation and run it within the mill computing environment in real time. With the correct interface to the mill control software the simulation appears 'as the process' allowing us to test the actual control software in its target hardware off-line.

The Real Time Workshop is able to generate documented ‘C’ code from SIMULINK block diagrams. Future control strategies developed in SIMULINK as block diagrams could thus be converted and downloaded to the target hardware. This facility is currently being used in a number of safety critical areas and has been partially tested at the CPM.

## CONCLUSIONS

- A comprehensive simulation has been developed that combines models of the behaviour of the hot strip in the roll gap and interstand with the finishing mill machine dynamics and controller functions.
- The numerical solution method for the coupled interstand, rollgap and looper equations, borrowed from fluid dynamics, has been found to be very robust allowing coarse space/time discretisation. The simulation for six stands runs in about twice real time on a 500MHz PC.
- Extensive use is made of SIMULINK S-functions, coded in ‘C’ for speed, to represent certain aspects of the finishing mill. Actual mill control computer code could be incorporated into the simulation.
- Graphic tools in MATLAB such as plotting and animation have been crucial to visualisation and understanding of simulation results.
- Facilities to generate real time code offer significant potential benefits such as hardware in the loop testing of improved control algorithms and automatic generation and documentation of control code for target hardware.


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‘Corus’ is the trading name of British Steel Ltd who undertook this research.