CHAPTER 2

PROCESS DESCRIPTION

2.1 Introduction

The general production route for steel consists of three stages of processing. They are iron making, steel making and making of rolled products [16]. Iron making can be grouped into two main routes, namely the blast furnace route to produce pig iron and the direct reduction route to produce direct reduced iron (DRI). In steel making there are again two routes. They are the basic oxygen furnace route and the electric arc furnace route to produce steel from pig iron, DRI or scrap. In secondary steel making additions are then made to the steel before slabs, billets and blooms are produced from it during continuous casting. This chapter covers a discussion of modeling variables and an outline of the modeling theory, which is given in order to show how some variables are related to the process. In addition the structure of the simulator, reported on in [4], is discussed and an overview of control in rolling mills is given. First however, a description of the hot rolling process follows with the focus on the finishing mill, the Steckel mill.

2.2 Hot Rolling Process Flow

The hot rolling process flow is illustrated in Fig. 2.1. Each step in this process is described below [4].

- Slab reheat furnace: For slabs coming from continuous casting this is the first stage in the hot rolling process. In this furnace the slabs are reheated and kept at a temperature of between approximately 1100 to 1250 °C. When proceeding to the rougher the slabs leave the furnace at a preset temperature calculated by the setup program. The value of the measured temperature is then used to calculate the settings of the rougher.

- Primary descaler: This stage starts with descaling the slabs by means of high pressure water jets. Without descaling surface defects can be caused in the roughing mill when scale is rolled into the slabs' surface.

- Secondary descaler 1: The function of the secondary descaler is to remove secondary scale and improve the smoothness of the slab surface before it is rolled in the rougher.

- Vertical edger: The edger reduces the slab in width to prevent excessive material spread through plastic deformation such that it leaves this stage with a dog-bone shape cross section [15].

- Horizontal roughing mill: The roughing mill consists of a vertical edger forming an assembly with the reversing horizontal stand [1]. Its purpose is to reduce the slab to an intermediate thickness of 22 to 32 mm.

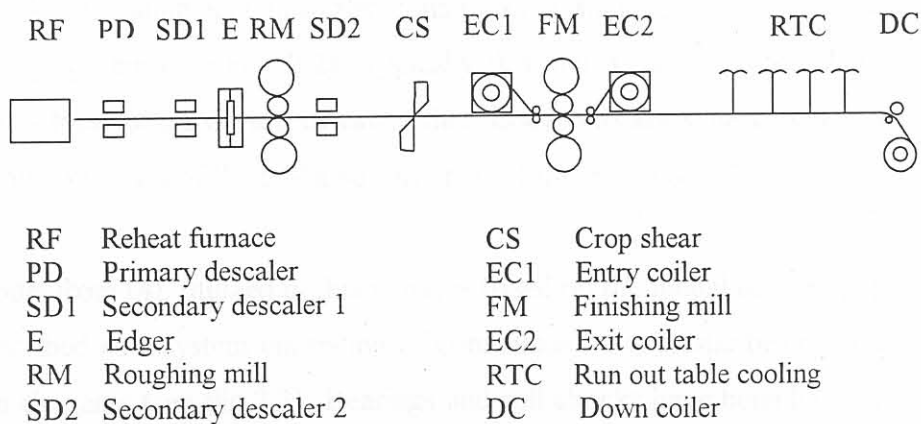| RF | Reheat furnace | CS | Crop shear |
PD	Primary descaler	EC1	Entry coiler
SD1	Secondary descaler 1	FM	Finishing mill
E	Edger	EC2	Exit coiler
RM	Roughing mill	RTC	Run out table cooling
SD2	Secondary descaler 2	DC	Down coiler

Figure 2.1: Hot rolling process

- Secondary hydraulic descaler 2: Secondary descaling can be used after roughing before the plate enters the final rolling. Secondary descaling is also done with high pressure water jets.

- Crop shear: Head and tail ends can have defects caused during roughing. In order to have them removed before the plate enters the finishing, the ends are cropped.

- Entry coiler: The entry coiler is situated in a furnace to maintain the temperature level needed during rolling. It is part of the finishing mill. After every pass the entry coiler changes to exit coiler and vice versa.

- Finishing mill: This is where the Steckel mill is used to reduce the strip to its desired thickness in a reversing action whilst maintaining the strip profile and shape.

- Exit coiler: The description for the entry coiler also applies to the exit coiler.

- Run-out table cooling: As soon as the strip is at its specified gauge, it is cooled such that the materials micro structure is fixed and therefore also its mechanical properties.

- Down coiler: After completion of all steps in the rolling process the strip is coiled ready for packaging or for secondary manufacturing processes.

2.3   The Steckel Finishing Mill

2.3.1   Design

The Steckel finishing mill basically consists of a stand carrying rollers and a hydraulic positioning system (see Fig. 2.2). Typically this mill is built as a four high type, meaning that it has four rollers on top of each other. Load cells are situated below the rollers. The coilers on both sides of the mill also form part of the finishing mill.

The model from [4], utilized in this work, is based on the model derived in [17] in so far as it is described as a system consisting of continuous mass elastic beams held in position by discrete elements (see Fig.2.3). Bearings and roll chocks have been lumped and termed as discrete elements. They are approximated by discrete lumped masses and springs indicated as Ms and Ks respectively in Fig. 2.3. In the model, work rolls and back up rolls have been described as continuous mass beams subjected to elastic bending. Bending of the work rolls is diminished by the use of back up rolls. The top and bottom back up roll bearings are supported by means of hydraulic actuators and load cells respectively. The rolling force is transmitted through the roll necks to the actuators at the top and load cells at the bottom of the mill and is absorbed by the mill frame as elastic stretch. Hydraulic jacks are

mounted between the bearings of the top and bottom work rolls on the drive, and on the operator side of the mill indicated as springs K_{JL} and K_{JR} in Fig.2.3. Their function is to counteract bending moments on the work rolls caused by the separating force of the strip. It is the function of the hydraulic actuators to move the backup rolls such that the roll gap is kept constant.
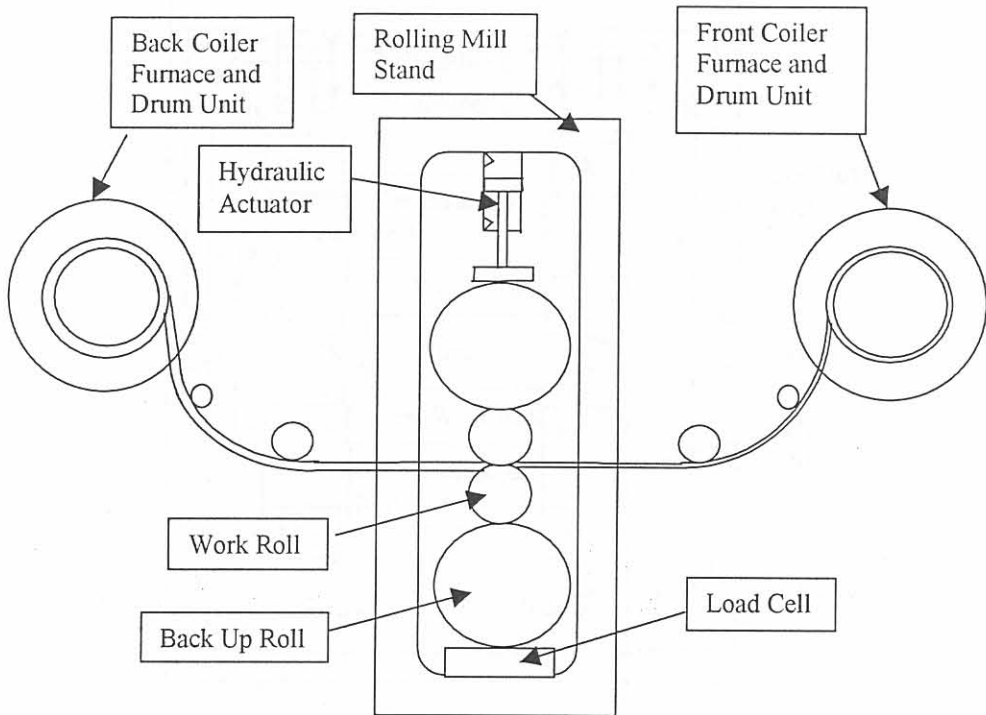
Figure 2.2: Side view of a Steckel hot rolling mill.

2.3.2   Principle of Steckel Hot Rolling

After the strip has been cropped ahead of the Steckel mill, the strip head end is passed underneath the entrance coiler furnace and threaded into the roll gap by the entry side pinch roll unit. After the first pass the strip is fed to the delivery side coiling mandrel and as soon as the first wraps have been coiled and the strip tension has assumed its setup value, the coiler accelerates together with the mill [2]. A constant strip tension is maintained during a pass. When the tail end of the strip enters the roll gap, the mill is slowed down such that the tail end stops before the pinch roll unit on the current delivery side of the mill. The roll gap is then preset for the next pass and the process is reversed

such that the entry side pinch roll unit now feeds the entry side coiling mandrel. The nature of this reversing process is such that the ends of the strip are exposed to greater cooling because the process involves braking, feed into the roll gap and threading in. Therefore the rolling force increases when the strip ends move through the roll gap. This is a characteristic of Steckel hot rolling mills.
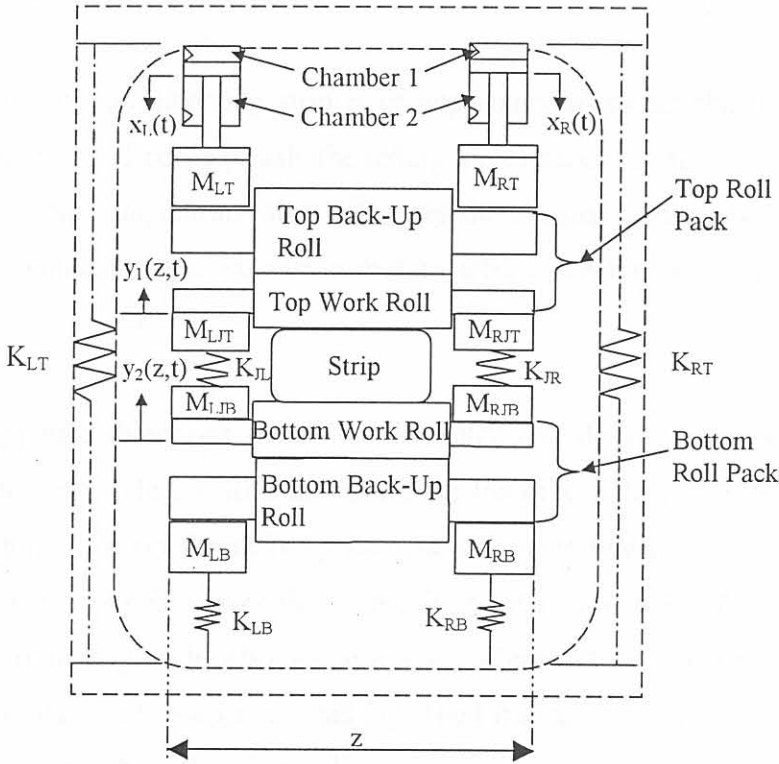

Figure 2.3: Cross sectional view of rolling mill (figure adapted from [4]).

2.3.3 Roll Gap Physics

Across the roll gap the law of mass flow continuity holds [18]. With the assumption that material spread in the width is negligible it can be stated that:

$$v_1 \cdot h_1 = v_2 \cdot h_2 \qquad (2.1)$$

where

v_1 : strip's entrance velocity into the roll gap,

h_1 : strip's entrance thickness into the roll gap,

v_2 : strip's exit velocity from the roll gap and

h_2 : strip's exit thickness from the roll gap.

In the roll gap metal flows plastically. Because of this plasticity of the material the whole roll gap is filled with strip material. The strip entering the finishing mill has a temperature of more than 1000°C. In the roll gap the entering strip exerts a separating force, the specific roll force P' in [N/m], on the work rolls causing them to bend and the arc of contact to flatten elastically. Due to bending of the rollers the strip leaving the roll gap is slightly thicker along the center. This deviation of strip thickness across its width is termed the crown.

The temperature of the incoming strip is of importance in so far that the material yield stress depends on it and consequently the rolling forces necessary for a certain reduction in thickness. The strip temperature also influences the thermal crown on the working rolls and their differential thermal expansion in turn affects the thickness crown of the strip ([2],[19]).

Slipping in opposite directions occurs at the entry and delivery side along the arc of contact. At the entry side the strip moves slower than the rollers such that it gets drawn into the roll gap while on the delivery side the strip gets braked because the peripheral speed of the work rolls is slower than the exit speed of the strip. This phenomenon of friction forces opposing each other along the arc of contact and increasing in a direction towards the roll gap lead to a friction hill [7]. The location of this friction hill is called the neutral point, a point where there is no slip.

It is possible to shift the position of the neutral point by applying back tension, T_1, which is strip tension between the entry coiler and the stand, and front tension, T_2, which is the tension between the stand and the exit coiler. The application of back tension moves the neutral point towards the roll gap exit while front tension shifts it towards the entrance [7]. It is known that back tension is more effective in shifting the neutral point than front tension [20].

2.4   Variables

2.4.1   Modeling Variables

Variables that are significant in the rolling process and that have been used in the modeling work of Scholtz [4] are mentioned below, the purpose of which is to give a more detailed description of the process. Some variables affect the deformation in the roll gap directly and some indirectly.

Temperature θ : Temperature is an independent process parameter [7] and is regarded as a key variable [10] in the deformation of metal as it influences the yield stress, which is also dependent on strain and strain rate of the material.

Friction coefficient μ : The friction coefficient, which was in [4] computed as a linear function of temperature of the material in the roll gap, affects the force balances in the derivation of Orowan's differential equation [5]. It is by means of this equation that the specific rolling force, P', which was already mentioned in section 2.3.3, is determined.

Vertical pressure p : The vertical pressure distribution along the arc of contact between the strip and the rollers depends on the deformed roll radius and is influenced by the independent variables [7], and front and back tension.

Deformed roll radius R' : Part of the geometry of the roll gap is the deformed roll radius. While exerting roll pressure onto the strip the rolls tend to deform which results in an increase in the roll radius in the arc of contact [22]. An interdependency exists between the deformed roll radius R' and the specific rolling force P'.

Rolling velocity v_{roll} : The rolling velocity is an independent process parameter [7] and it influences the strain rate in the roll gap and the front and back tensions of the strip.

Entrance velocity v_1 (see Fig. 2.4): The entrance velocity of the strip into the roll gap is determined by the material flow $h_1 v_1$ entering the roll gap.

Exit velocity v_2 (see Fig. 2.4): The exit velocity of the strip depends on the material flow $h_1 v_1$ as well as on the reduction in thickness, known as draft, $\delta = h_1 - h_2$.

Back coiler peripheral speed v_{bc} (see Fig. 2.5): The back tension T_1 is influenced by the difference between v_1 and v_{bc} via an integral relationship.

Front coiler peripheral speed v_{fc} (see Fig. 2.5): The front tension T_2 is influenced by the difference between v_2 and v_{fc} via an integral relationship.

Draft δ: The draft is used to calculate the bite angle and the horizontal length of the arc of contact and indirectly determines the specific rolling force P'.

Yield stress k: Yield stress is a function of strain rate and temperature of the material. Elastic regions exist before and after plastic regions in the roll gap [23] and can be attributed to the yield stress, which is higher than the local applied stress.
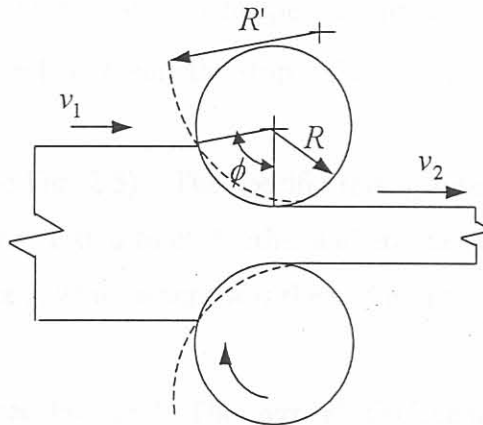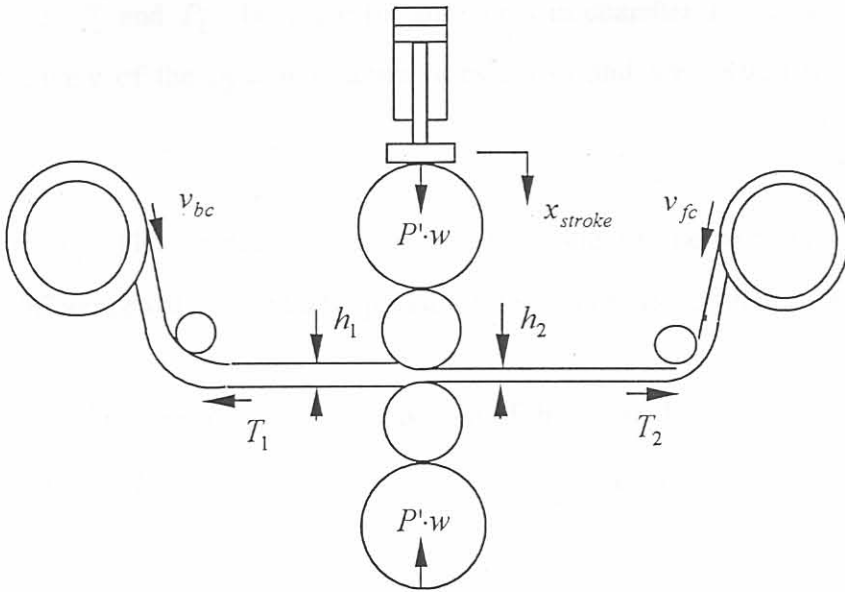

Figure 2.4: Roll gap variables.

Figure 2.5: Rolling process variables.

Back tension T_1 (see Fig. 2.5): Regarding the deformation process back tension is an independent process parameter [7] braking the material flow into the roll gap.

Front tension T_2 (see Fig. 2.5): It is also an independent process parameter with respect to the deformation in the roll gap [7] causing the strip to be drawn.

Specific rolling force P' (see Fig. 2.5) : The specific rolling force and vertical pressure in the roll gap are proportionally related to each other and are the result of hydraulic actuator stroke. The total rolling force is $P' \cdot w$, where w is the width of the strip.

Vertical displacement y_1 (see Fig. 2.3): The vertical displacement y_1 of the upper roll pack consisting of the upper work and backup roll is determined from a force balance of the seperating force of the strip and the forces exerted by the hydraulic jacks and roll chocks, i.e. the discrete elements in the modeling work in [4], onto the roll pack.

Vertical displacement y_2 (see Fig. 2.3): This is the vertical displacement of the bottom roll pack consisting of the bottom work and back up roll and it is also determined from a

force balance of the seperating force of the strip and the forces exerted by the chocks and hydraulic jacks onto the roll pack.

Cylinder pressures P_1 and P_2: They are the pressures in chamber 1 and chamber 2 (see Fig. 2.3) respectively of the hydraulic actuator cylinders and are related to the specific rolling force P'.

Supply pressure P_s: This pressure is on the supply side of the hydraulic positioning system and its difference with the cylinder pressures determines the cylinder flows.

Tank pressure P_t: This pressure is on the tank side of the hydraulic positioning system and its difference with the cylinder pressures determines the cylinder flows.

2.4.2   State Variables

The state space model of the Steckel hot rolling mill process comprises 18 state variables. The first eight state variables represent the normal time coordinates $q(t)$ of the stand and their derivatives $\dot{q}(t)$. Together with the assumed modes, $\psi(z) = [\psi_1 \quad \psi_2]$, vertical displacement $\hat{y}_i(z,t)$, $i \in [1,2]$, of the roll packs can be expressed as:

$$\hat{y}_i(z,t) = \sum_{j=1}^{2p} \psi_{i_j}(z) q_{i_j}(t) = \psi_i(z) q_i(t) \qquad (2.2)$$

with the assumed modes vectors, $\psi_1(z)$ and $\psi_2(z)$, as described in section 2.5.1.

The other 10 state variables describe the state of the hydraulic positioning system by means of hydraulic pressures, hydraulic stroke, servo valve openings and the derivatives of servo valve openings. The part of the model described by these 10 variables forms the nonlinear part of the state space model.

2.5   Simulator

2.5.1   Models

As it became obvious in the previous sections, the rolling process is ruled by different aspects such as the strip tension on both sides of the roll gap, the hydraulic actuators exerting forces on the rollers, the stand which consists of rollers changing their position thereby influencing the roll gap and the material in the roll gap itself. In order to take all these aspects into account in a simulator of the process, four core models were derived in [4]. These models are the roll gap model (RGM), the tension models (TM), the stand model (SM) and the hydraulic actuator model (HA), which together form the simulator. They are described below in terms of their inputs, outputs as well as the theory the models are based on.

Roll gap model: For the RGM the draft, δ, roll speed , v_{roll}, entrance and exit temperatures, θ_1 and θ_2, and entrance and exit tensions, T_1 and T_2, are the inputs while the specific rolling force, P', entrance and exit velocities, v_1 and v_2, and the length of the arc of contact, L_p, are the outputs, i.e. the values calculated from the input values.

P' in [N/m] is computed from the vertical rolling pressure, p in [Pa], which is determined by solving the following ODEs.

$$\frac{dp}{d\phi} = \frac{2R'}{h(\phi)}\left[p(\phi)\left(\frac{\sin\phi \pm \mu\cos\phi}{1 \mp \mu\tan\phi} \right) - p(\phi) - k)\sin\phi \right] \tag{2.3}$$

where

ϕ : angle of arc of contact measured from the exit of the roll gap in [rad] (see Fig. 2.4),

h : strip thickness [m].

P' is also a function of R' [24] which in turn depends on P' by the relationship of Hitchcock's formula given as

$$R' = R\left[1 + \frac{16(1-\upsilon^2)P'}{\pi E\delta} \right] \tag{2.4}$$

where

υ: Poisson's ratio for steel and

E: Young's modulus of the work rolls.

The structure of the RGM is an iterative loop with a relaxation step for R' because of this implicit relationship between P' and R'. In this loop R' is updated and the two ODEs in Eq. 2.3 are solved.

Tension model (TM): The TM describes the strip tension behaviour during the rolling process. The inputs of the TM are v_1 and v_2 from the RGM as well as v_{bc} and v_{fc}, the back and front coiler speeds respectively. A change in draft, δ, results in a change in v_1 and v_2 and therefore in tension variations according to

$$T_i = \frac{E_{ss}(h_i w)}{L_{cfrg}} \int_0^t (\pm v_i(\tau) \mp v_c(\tau)) d\tau \tag{2.5}$$

where

$i \in [1,2]$, $v_c\big|_{i=1} = v_{bc}$, $v_c\big|_{i=2} = v_{fc}$,

E_{ss}:   Young's modulus of strip material,

w: width of the strip,

L_{cfrg}: strip length between coiler furnace and roll gap.

At a given instant T_1 and T_2 are determined iteratively in a loop in which $T_i, i \in [1,2]$ is updated and which contains a relaxation step for T_1 and T_2. As soon as the tension has stabilized in the iteration loop, time is incremented by $\Delta t_{tension}$ and the iteration for T_1 and T_2 in the next time step is repeated. The integrals of Eq. 2.5 are computed in every execution of the iteration loop.

Stand model (SM): Elastic stretch of the mill stand and roll bending are the phenomena that are described by the SM. Its inputs are P' across the width of the strip and the cylinder chamber pressures of the hydraulic actuators ($P_{L1}, P_{L2}, P_{R1}, P_{R2}$ in [Pa]) where L and R denote left and right respectively and 1 and 2 denote the chambers. This model has a draft deviation as output, which is calculated as

$$\delta(z,t) = \delta_{setup} - (\delta h_1(t) - (y_1(z,t) - y_2(z,t))), \qquad (2.6)$$

where

$$-\frac{w}{2} \leq z \leq \frac{w}{2}.$$

By means of separation of the dependency on the variables t and z with an assumed modes vibration analysis method, a decoupled normal coordinate system was derived in [4] to form the following linear ODE system.

$$\begin{bmatrix} \dot{q} \\ \ddot{q} \end{bmatrix} = \begin{bmatrix} I & 0 \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1}U^T B \end{bmatrix} u_{SM}, \qquad (2.7)$$

where

M : system mass matrix,

K : system stiffness matrix,

C : system damping matrix,

U : modal matrix,

B : input matrix and

u_{SM} : input vector to the SM $= \begin{bmatrix} P_{L1} & P_{R1} & P_{L2} & P_{R2} & P' \end{bmatrix}^T$.

B was derived in [4] as

$$B = \begin{bmatrix} -\psi_1^T(-\frac{l_1}{2})A_{L1} & \psi_1^T(-\frac{l_1}{2})A_{L2} & -\psi_1^T(\frac{l_1}{2})A_{R1} & \psi_1^T(\frac{l_1}{2})A_{R2} & \Delta_z\psi_1(z)^T \\ 0 & 0 & 0 & 0 & -\Delta_z\psi_2(z)^T \end{bmatrix}, \qquad (2.8)$$

where

l_1 : length of top roll pack,

ψ_1 : assumed modes vector for top roll pack,

ψ_2 : assumed modes vector for bottom roll pack,

A_{si} :   cylinder cross sectional areas with $s \in (L, R)$ and $i \in (1,2)$. L and R denote left and

right side of the stand and 1 and 2 denote top and bottom roll pack respectively.

Δ_z :   length of one of the 51 elements into which a roll pack is divided along its length.

Hydraulic actuator model (HA):   The inputs of the HA are the left and right hydraulic stroke set points and the outputs are the left and right hydraulic strokes of the actuators. The HA is integrated into the simulator by the relationship that exists between the hydraulic stroke, the vertical displacement of the upper roll pack and mill stretch. In addition the derivatives of the cylinder pressures are expressed in terms of state variables, namely cylinder pressures and vertical displacement derivatives of the upper roll pack showing how the HA is linked to the SM. The relationships that describe the behaviour of the hydraulic actuators are based on the continuity laws of the fluid flow in them as well as on second order dynamics of the servo valve opening (spool movement).

2.5.2   Simulator Structure

Two dynamic models and a static model constitute the simulator. The two dynamic models are the tension model and the state space model. The latter is formed by the stand and hydraulic actuator models. Since the problem solved by the RGM is an off-line analysis problem [5] with computation of force under static conditions, the RGM, which is based on Orowans roll gap theory, can be regarded as a static model. It is recommended by [4] that the tension model is simulated at a higher sampling rate than the main time advancement of the simulator in order to keep the tension loop stable, i.e. values for tensions that converge have to be found iteratively before the tension values for the next time step of the tension loop can be computed.

Referring to Fig. 2.6, the simulator is started by reading input files. It then calculates the initial conditions. At the very beginning of a simulation the initial conditions are determined from steady state values because the simulation is not started before commencement of rolling, but after the pass has been partially completed. Also, before the main time advancement loop starts, the stroke caused by the cascaded hydraulic actuator controller is calculated for the set up of the initial piston extension. The combined actions of the initial set up of the piston extension and the gauge meter compensator are then determined and taken into account in the state space model.
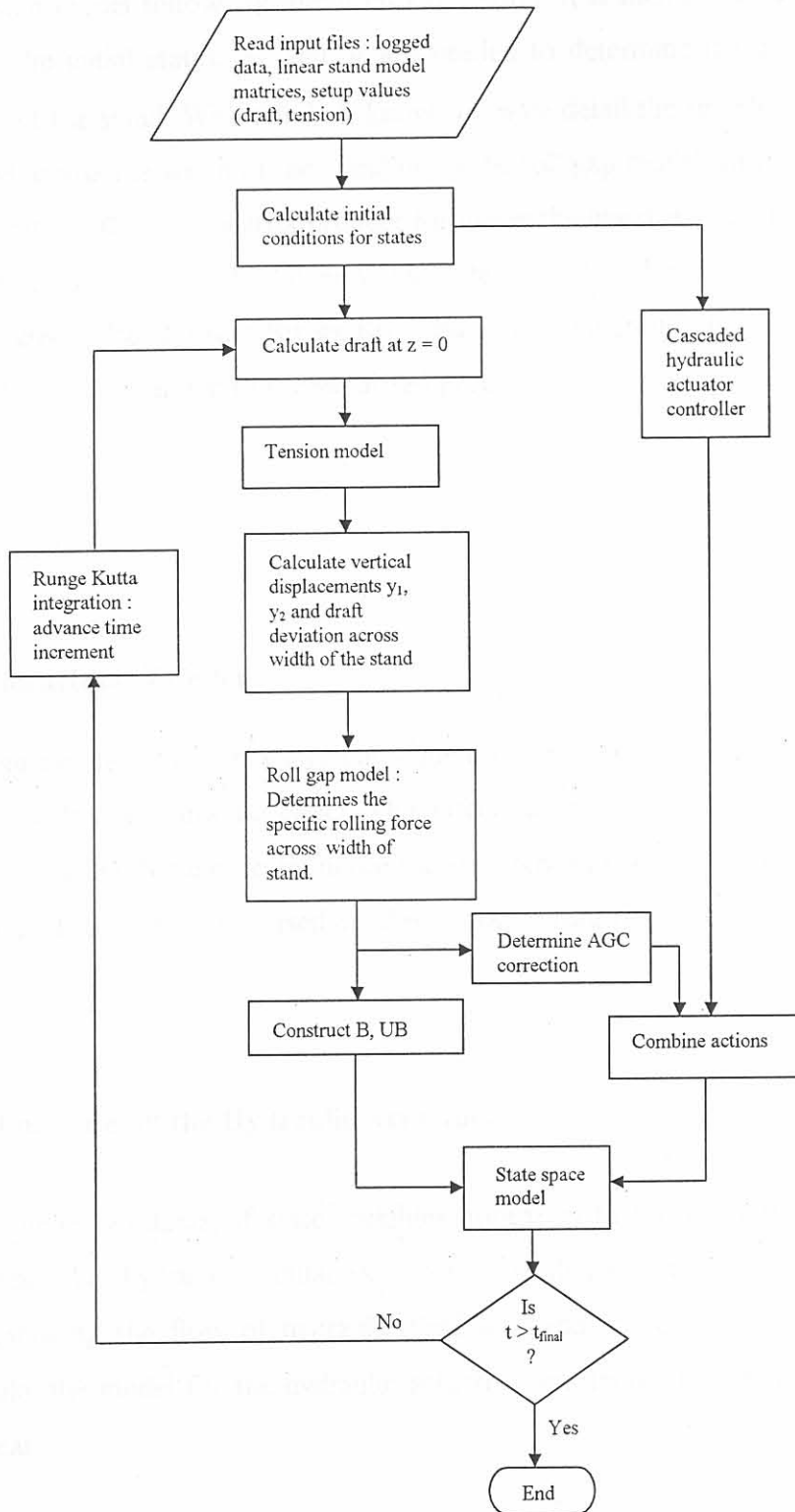
Read input files : logged data, linear stand model matrices, setup values (draft, tension)

Calculate initial conditions for states

Cascaded hydraulic actuator controller

Calculate draft at z = 0

Tension model

Runge Kutta integration : advance time increment

Calculate vertical displacements y_1, y_2 and draft deviation across width of the stand

Roll gap model : Determines the specific rolling force across width of stand.

Determine AGC correction

Construct B, UB

Combine actions

State space model

Is t > t_{final} ?

No

Yes

End

Figure 2.6 : Mill simulator flowchart (figure adapted from [4])

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The main loop of the simulator starts with a calculation of the draft, which is necessary because the draft is an input to the roll gap model, which in turn is a part of the tension model. The tension model follows on the draft calculation. It is then possible to compute y_1 and y_2 from the initial states. y_1 and y_2 are needed to determine the draft deviation across the width of the stand. With the draft known in more detail the specific rolling force can be calculated across the width of the stand using the roll gap model. In the subsequent steps the input matrix, B, and a matrix product for use in the linear part of the state space model are formed (see Fig. 2.6). All new 18 states, i.e. for the next time step, are integrated by means of fourth order Runge Kutta numerical integration from the old states before the next time advancement of the simulated process.

2.5.3   Nonlinearities

2.5.3.1   Nonlinearities of Coilers

Due to the large moment of inertia and consequently very slow response of the coilers their behaviour exhibits a saturation effect. This effect can be expected when a change in coiler speed is demanded for e.g. to influence the strip tensions. Because the coiler inertia does not form part of the model used in this work, saturation in coiler speed is not considered here.

2.5.3.2   Nonlinearities of the Hydraulic Actuators

Terms which contain products of state variables appear in that part of the state space model describing the hydraulic actuators. More specifically these terms appear in expressions describing the flow of hydraulic fluid into and out of the cylinders. These expressions make the model for the hydraulic actuators and therefore the entire model of the mill nonlinear.

2.5.4   Control Systems of Hot Rolling Mills

2.5.4.1   Introduction

Common control systems for hot rolling mills are discussed in this section. The following control system architecture applies - besides other manufacturing processes - also to hot rolling [15].

i)   Level 3: Plant wide control. This includes production planning and scheduling.

ii)   Level 2: Supervisory control. It includes set-up and control strategy selection.

iii) Level 1: Dynamic control. It is concerned with closed loop control parameters such as exit gauge, strip temperature, profile and shape of the material to be rolled, i.e. it is concerned with the process itself.

The overview of control systems given in the sections to follow will focus on level 1 control.

2.5.4.2   Automatic Gauge Control

As mentioned in the first chapter it is one of the main objectives of hot rolling to maintain a constant thickness for the rolled strip. Disturbances that can prevent this objective from being achieved can be of two different kinds [15].

i)   Disturbances arising from the incoming strip, such as gauge or yield strength variations.

ii)   Disturbances arising from mill equipment, such as roll eccentricity, roll expansion and roll wear.

The difficulty associated with thickness measurement, which would be necessary for thickness control, is that it cannot be done directly at the location where reduction in thickness takes place. Information about strip thickness can however be derived from load force measurements. The British Iron and Steel Research Association (BISRA)-Davy gauge meter [15] makes use of this principle by which the roll force is manipulated to control the strip exit gauge. It is used on multi stand as well as on Steckel type hot rolling mills.

The relationship between roll force and gauge is linear over a significant range of roll force values. In its linearized form the relationship is.

$$\delta h_2 = -\delta x + \frac{\delta F}{M} \qquad (2.9)$$

where M is constant and

δh_2 :   strip exit gauge,

δx :   hydraulic actuator stroke,

δF :   roll force and

M :   mill modulus.

The aim is to keep $\delta h_2 = 0$ such that $\delta x = \delta F / M$. A correction in δx can thus be made with exact knowledge of M. Compensation of initial condition errors and drift in the gauge meter thickness estimates is done by means of X-ray gauge measurements on the delivery side of the mill.

The output of the automatic gauge control system, also called gauge meter compensation, is a position reference, which is used by the actuators to position the rolls such that a rolling force is effected. The actuators can either be electrical screw down or hydraulic capsules.

2.5.4.3   Mass Flow and Tension Control

Tension control of Steckel mills will be considered eventually but first a look will be taken at tension control of multi stand rolling mills. However, because the same device, the looper arm, is used for tension control as well as mass flow control, i.e. two control functions, both will be explained briefly.

These two functions of loopers are:

i)   They prevent width and thickness changes by means of tension control.

ii)   They prevent the formation of strip loops between stands by regulating mass flow.

Strip tension is controlled by torque of the looper motor. Torque is changed by manipulating the motor current. This control is thus indirect. The looper angle is the angle, which the looper arm makes with the horizontal. This angle is an indication of the mass flow. Mass flow is regulated by manipulating the speed of the upstream stand drive motor.

Via the looper both control functions take place close to each other: The looper angle influences the loop length and torque on the looper axis affects the tension. Yet, it is common that tension and loop length (mass flow) are controlled independently.

Mass flow control:

Before and during threading of the strip the set up velocity is the reference velocity. At threading speed it can be trimmed by the mass flow controller, the temperature controller or by zooming. Zooming is the speed increase of the strip in order to minimize temperature losses. The choice of the set up velocities depends on the gauge reduction schedule. If the mass flow has to be increased the looper angle is increased by a speed up of the upstream stand drive motor. Initially this will result in a reduction of the strip tension causing the looper motor to supply more torque. Even if the error in looper angle is zero the looper motor will have its current increased to increase the torque such that the tension reference is achieved.

Tension control:

The problem with tension control in multi stand mills is that no direct measurements of tension are possible and are therefore not available. This makes tension control more complicated. Instead the looper angle is used to calculate the torque required to maintain the tension at the desired reference level. The torque applied at the looper axis is needed not only to oppose the moments caused by strip tension, but also the moments due to the weight of the strip, looper arm and roll as well as the bending of the strip. The sum of these components therefore constitute the reference torque. Each one of these components is a function of the looper angle [15].

The reference torque is the torque needed to regulate the tension at a reference value at the current looper angle. This torque changes in accordance with the looper angle. The reference torque cannot be determined exactly with equations available because of errors in physical assumptions that result in physically wrong equations. Also strip width, gauge and yield stress are not exactly known at each time instant. By means of the current feedback loop the reference torque, which is an input to the looper motor, is maintained. More difficulties in maintaining tension arise during acceleration and deceleration phases of the looper motor. Interaction between looper angle and tension makes independent control of mass flow and tension difficult and multivariable control necessary.

2.5.4.4   Steering Control

Because reversing mills, such as the Steckel mill, are particularly intolerant to camber errors in comparison with tandem mills, steering control is used in Steckel mills. For this control system the measurement system consists of two single-sensor (mono-scopic) Charged Coupled Device (CCD) cameras one each at the mill entry and exit. These two cameras are used in addition to another pair of CCD cameras in a stereo-scopic configuration.   The mono-scopic cameras take independent measurements of the strip centerline while the stereo-scopic cameras provide an accurate measurement of the finished width and centerline position [35].

Depending on the strip centerline deviations from the centerline position of the mill a differential roll gap correction is applied. In order to avoid worsening the capability of the mill to maintain constant strip thickness across the width of the strip, the automatic steering system does as little as possible to keep the strip centered.

The conventional method of automatic steering in reversing mills is to apply a differential roll gap correction based on a measured differential load. This method is however only effective if the source of the error is a temperature difference across the width of the strip. The controller will then tend to command a higher force on the side of the strip with the higher resistance to deformation and in doing so ensuring equal elongation over the width of the strip, keeping it straight. When the measured load difference is caused by a wedge profile of the strip unequal elongation will take place, producing a cambered bar.

2.5.4.5   Profile and Flatness Control

The profile and flatness control system present in Steckel mills is used to counteract the influence of progressive wear and thermal crowns on the work rolls as well as changes in roll force due to temperature variations of the strip.

Because changing the profile in thinner strips would also result in flatness errors, profile modifications are done during the first passes while during the last passes it is kept constant to also assure flatness. These demands are met by use of a CVC (Continuously Variable Crown) system in combination with a work roll bending system.

Part of the CVC system are work rolls with S-shaped barrel contours and with the rolls in a diametrically opposite arrangement. The work rolls can be shifted in opposite directions in order to change the crown. Depending on whether a positive or a negative crown is desired the shifting direction is changed accordingly.

Another precondition for a profile and flatness control system is an efficient computer model by means of which preset values for the CVC system and the work roll bending system can be determined based on data for each pass such as strip width, strip thickness and rolling force. Also included in this data would be the desired strip profile.

The function of the automatic profile control (APC) then is to keep the roll gap contour – and thus the strip profile – constant over the length of the strip in the presence of varying rolling forces. Because on Steckel mills extreme differences in rolling force can occur, it happens that the setting range of the work roll bending system is not always sufficient. When it happens that the predetermined bending force is reached the CVC system automatically shifts the rolls, preventing the bending system from reaching its limits [27].