Hydraulic Screwdown Control Systems for Cold Mills

Hydraulic screwdown control systems for cold mills have must be capable of the following tasks:

1. Strip thickness control
2. Roll force control
3. Strip tension control

While the strip thickness control system is responsible for the accuracy of the gauge at the exit side of the mill, the roll force control ensures a constant mill pressure during the rolling process. The strip tension control is applied in the thin strip range, when a deformation of the material is no longer possible via the thickness control because the work rolls contact each other at the ends. The required strip thickness changes are achieved by a strip tension change in this case.

In order that the mill be able to perform these strip thickness and roll force functions, it is necessary to use servo controlled hydraulic screw down cylinders due to their high response time to control signals. Properly designed, these cylinders are able to achieve and maintain the highest degree of control.

In practice, the recording of the mill characteristics (roll force change in dependence of the screwdown range), is used to verify that the mill has been optimally tuned.

Figure 1) Mill Characteristics:

The dimensioning of the actuators and sensors is of vital importance.

The resolution, accuracy and repeatability of the sensor are particularly important. Good control results can only be achieved with very good measurement. The same applies to the control elements.

Not all actuators and sensors, available on the market, are able to cope with the rough requirements of cold mills so that the proper selection of the suitable components is vital to achieving acceptable mill reliability.

External factors impair the control quality immensely so that the technical conditions of the mills, such as roll concentricity, input material characteristics (hardness, shape, step thickness changes, etc.), strip tension stability, to name just a few, are of enormous importance.

Countermeasures to reduce the effects of these factors are available. Normally, specific factors can entirely or partly be compensated for by the proper selection of the available control modes (described below); in addition, measures to detect interference factors offer an effective solutions (such as spike suppression for step changes or FFT analysis in case of repetitive faults).

When the hydraulic screwdown control (strip thickness or roll force control) has been selected, the optimum control mode must be found for the particular application. We differentiate between the so-called basic strip thickness control modes (inner loop)

A. Roll gap control
B. Position control

Plus the additional controls. The following additional controls are available:

a. Feedback control
b. Feedforward control
c. Mass Flow (constant volume) control
d. Elongation / Reduction control
The operation of the different control modes (strip thickness and roll force control) and the logical combinations of controls are described below.
Roll Gap Control

The roll gap control is based on measurement sensors, measuring the distance between the lower and upper work roll directly. The feelers of the roll gap sensors contact the work rolls on the so-called measurement rings:

Based on the direct roll gap distance measurement, this basic control mode reacts to any changes in the roll gap. Effects of the mill extension (housing acts as a spring) do not affect the roll gap measurement.

The deviations from the nominal value, detected by the two roll gap sensors, are sent to the servo valves via the PID controllers and servo amplifiers.

Various adjustment speeds are available for nominal value changes. The synchronization between the drive side and operator side roll gap sensor is guaranteed. The maximum stroke is monitored. With the manual screw down commands (such as drive side up, operator side down), a tilt monitor prevents exceeding the preset control limits.

The distance variation from the preset size, detected by the spring-loaded feelers in the roll gap sensors cause a change of transducer (LVDT) values. The standardized analog voltage (e.g. 10 mV/µm) is generated in the amplifier by a phase sensitive rectification and sent to the controller. The limited measurement stroke of the transducer requires a stepper motor that will bring the transducer into the required working range.

The stepper motor motion can optionally be monitored by an incremental sensor mounted at the rear of the motor.

The roll gap control reacts in case of a dimensional variation in the roll gap. Depending on the current mill speed and the mill response time (total of control variation, such as mill extension, screwdown speed, bearing play, roll flattening etc.), dimensional variation is limited by the reaction time of the mill components.

The quality can be improved by a combination with additional controls such as feedback, feedforward or constant volume control.

If the mill has a roll bending control, during which the work rolls are bent, a suitable compensation of the roll gap sensor signals will be necessary by reading the actual values from the proportional valves.

The roll gap control has advantages versus the position control. The roll gap measurement is much more sensitived since the position sensors, mounted on the screwdown cylinders, only measure indirectly, thus erroneously, due to the mill extension, bearing play etc.

The control advantages of the roll gap control system, higher expenses due to the maintenance (regular exchange of feelers) and work roll grinding (body and measurement ring), compared with the position control, can be accepted. The Roll Gap Control is especially effective when the entry material thickness is impossible or very difficult to measure.
Figure 6) Roll gap sensor:

Technical Data:

- **Type:** Vollmer Gap Sensor
- **Class of Protection:** IP 67
- **Accuracy:** 1 µm
- **Resolution:** < 1 µm

Figure 7) Block Diagram of roll gap control:

General chart gap control

Basic control loop:
- gap control

- $h_\text{in}$: Ingang Thickness
- $h_\text{out}$: Outgoing Thickness
- $F_w$: Sum RollForce
- $C_m$: Material evaluation ($F_w/h_\text{in}$)
- $C_g$: Mill constant ($d/\text{verb}$)
Position Control

In position control, the sensors are tightly connected to the screwdown cylinders by a measurement rod in most applications. This arrangement is often seen in two-high or 4-high mills. With so-called multi-roller mills, position sensors are often mounted laterally on the top or bottom. Both arrangements create errors since they do not measure the direct roll gap. For example, the mill extension must be considered; and the geometrical mounting must be noted.

High-resolving incremental sensors or absolute value sensors have proven to be successful as measurement sensors. The absolute value sensors have the advantage always to detect the current position. Incremental sensors detect relative position changes so that they need a reference calibration for the measurement of the position and the mill tilt (difference between drive side and operator side cylinder position).

Depending on the type of mill, 1, 2 or 4 position sensors are applied. The range to be measured depends on the screwdown stroke of the cylinder. Long-stroke cylinders are applied more frequently as a substitute for a prepositioning system with electric motor and short-stroke cylinder, as had been used previously.

Various adjustment speeds are available for nominal value changes. The synchronization between the drive side and operator side roll gap sensor is guaranteed. The maximum stroke is monitored. With the manual screw down commands (such as drive side up, operator side down), a tilt monitor prevents exceeding the preset control limits.

The position control only reacts if a deviation from the nominal size occurs in the roll gap and is detected by the position sensors. Depending on the current mill speed and the mill response time (total of control sections, such as mill extension, screwdown speed, bearing play, flattening etc.), the dimensional variation can only be controlled entirely at lower rolling speeds.

The sensitivity of the thickness deviations with the indirectly working position control is lower than with the roll gap control. Comparable good results as with the roll gap control can only be achieved by a combination with the feedforward control and/or the constant volume control.

Due to the mill extension, the adjustment of the nominal roll gap at the beginning of the pass is erroneous. This error can be reduced by the „Gagemeter“. The mill modulus is considered in the positioning. This procedure requires an estimate of the expected total roll force of the next pass.

Without the „Gagemeter procedure“, only the feedback control and constant volume control will help to achieve the required nominal thickness as quickly as possible.

High technical conditions are also required for the position control. The required thickness tolerances can only be achieved with extremely good roll concentricity accuracies.
Figure 8) Position sensor:

Technical Data:

Type: Heidenhain LS 106  
Class of Protection: IP 64  
Meas. stroke: 140 mm  
Resolution: 1 µm

Figure 9) Block Diagram of position control:

General chart position control

Basic control loop:

Position control

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Roll Force Control / Total Roll Force Control

Hydraulic-electric pressure transducers, mounted on the screwdown cylinders, are applied for the roll force measurement. These sensors convert a measured pressure to an electric signal (e.g. 0...10V or 0...20 mA). Direct measuring roll force sensors, mounted in the housing, spanning a distance and providing a measurement of the roll force via the housing extension, are seldom found.

The aim of the roll force control is to provide a constant pressure during the rolling process. I.e. entry side thickness variations are not controlled. In particular skin-pass mills, where large work rolls ensure a homogeneous surface in the last pass with low reduction, are often equipped with a roll force control.

There are two types of roll force control. The direct roll force control has the task to control each screwdown cylinder to a constant roll force. This type of control makes ‘mill steering’ difficult. If a strip moves toward the drive side, for example, the roll force on this side is increased (the operator side roll force is reduced). The control will reduce the drive side force, increasing the strip offset to the rear of the mill.

The total roll force control works in combination with the position control. The position control is active as the basic control mode. All roll force changes are detected as the sum of drive and operator side, are converted and sent to the position control loop as the nominal value change. I.e. roll force variations are always controlled parallel. With the above example, there would be no increase of the strip offset as the total roll force control remains constant.

External forces (such as bending, balancing) must be compensated for in the roll force measurement, especially when rolling loads are small.

The elongation control is applied as an additional control for the roll force or total roll force control. The feedback, feedforward or constant volume control cannot be combined with the roll force or total roll force control since these additional controls have an effect on thickness deviations and not on roll force variations.

The roll force control is also suitable for the detection of the roll concentricity accuracy. The total amount of errors of the applied roll set can precisely be measured, especially when roll gap sensors are installed. If only position sensors are available, then only the concentricity error tendency can be detected.

The roll force control is often applied as a protection against excessive roll forces. The roll force control will control with a preset nominal roll force (e.g. 80%) when these high values are reached.

The roll force control is also often applied for the calibration of the mill. The aim is to calibrate the mill with approximately the same roll force as will be used in production. The possible presets of the so-called „Calibration roll force“ are typically within a range of 10% - 90% of the total roll force.

Figure 10) SBlock Diagram of roll force control:

Technical Data:
Type: Hydraulic/electric transducer
Class of Protection: IP 67
Accuracy: < 0,1%
Output: 4 - 20 mA or 0 - 10 V DC
Feedback / High Gain

The feedback control, also known as „Monitor control“, is an additional control that is applied in combination with the roll gap or position control. The feedback control needs the online measurement signal of the exit side strip thickness gauge and the current mill speed. The distance between the roll gap and the exit side thickness gauge and the threshold values for the activation of the feedback control must also be preset.

The aim of the feedback control is to achieve and hold the preset nominal size of the exit side strip thickness within specific limits.

There are two types of feedback. At the beginning and at the end of the pass, usually with low strip speeds, the so-called „High gain“ is in operation. When activated with a measurement, this control detects the deviation between the nominal size and the current strip thickness, converts this signal with the mill and material evaluation and sends it to the basic control mode (roll gap or position control) as a nominal value correction (providing that the strip thickness gauge provides reasonable measurement values, the minimum strip speed threshold has been exceeded and the dimensional deviation of the thickness gauge is outside the preset tolerance values). The high gain waits until the changed strip thickness (in dependence of the current strip speed and the distance between roll gap and exit side thickness gauge) has reached the exit side thickness gauge and repeats the above process.

When the mill speed is increased, the high gain is replaced by the feedback control. This control mode principally works like the high gain, but the exit side thickness is not detected by a single measurement but by an average value formation via a preset distance (approx. triple work roll diameter).

Both types of feedback react in dependence of the distance. In practice, there is approx. 2-3 meters distance between roll gap and thickness gauge. When the feedback control is in operation, the distance of the average value formation is added. I.e. a control command is given by the feedback control only every few meters of material. Due to the described inertia, the bandwidth variation of the base material cannot be affected by the feedback control, only the trend line.

The feedback control can be combined with further additional controls, such as feedforward and/or constant volume control.

The threshold values are defined in dependence of the present nominal thickness:

<table>
<thead>
<tr>
<th>Nom. thickness:</th>
<th>Thresh. value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0,2 mm</td>
<td>+/- 0,5 µm</td>
</tr>
<tr>
<td>0,2 mm - 0,5 mm</td>
<td>+/- 1,0 µm</td>
</tr>
<tr>
<td>0,5 mm - 1,0 mm</td>
<td>+/- 1,5 µm</td>
</tr>
<tr>
<td>1,0 mm - 2,0 mm</td>
<td>+/- 2,0 µm</td>
</tr>
<tr>
<td>&gt; 2,0 mm</td>
<td>+/- 2,5 µm</td>
</tr>
</tbody>
</table>

The feedback control ensures an absolute accuracy to gauge of the exit side strip thickness. Since the strip thickness usually is the most important quality feature in the cold rolling process, the feedback control requires a thickness gauge that will satisfy these high demands.
Figure 11) Strip thickness gauges:

Figure 12) Block Diagram of feedback control:
Feedforward Control

The feedforward control is an additional control that is applied in combination with the roll gap or position control. The feedforward control needs the online measurement signal of the entry side strip thickness gauge and the current entry speed. The distance between roll gap and entry side thickness gauge and the mill response time (in practice detected via step response) must also be considered.

The feedforward control records the measurement values of the entry side thickness gauge, stores them in a shift register, which is cycled in dependence of the entry side strip speed, and sends these values, modified with the mill and material evaluation under consideration of the mill response time, to the roll gap or position control as a nominal value correction.

While the roll gap or position control can only react to thickness changes in the roll gap, the feedforward control causes required cylinder movements before the thickness changes are in the roll gap. The signals of the feedforward control act parallel on the screwdown cylinders of the drive and operator side.

The number of shift register slots is calculated from the distance between the entry side strip thickness gauge toward the roll gap, the current entry speed and the mill response time. Typical values are 8, 16, 32 or 64 register slots. Generally, the higher the number of slots, the better the result. To be noted in this connection: The entry side thickness gauge must have a sufficient measurement dynamics (integration time during measurement and preparation). The entry side strip speed measurement must also be extremely accurate. Incremental sensors, mounted on the deflector rolls or specific (nonslip) measurement wheels, with a resolution of >=5000 incr./revolution, or laser speedmeters with a similar resolution and accuracy are recommended here.

The gain factor of the feedforward control can automatically be adapted, i.e. optimally adjusted, via a check measurement of the exit side strip thickness gauge. Under consideration of the mill response time, the output values of the entry shift register are used as input values of an exit shift register which is cycled in dependence of the exit side strip speed. A comparison of the output values of the exit shift register with the current exit side strip thickness measurement value shows if the feedforward control signal is too low or too high. The evaluation of this difference automatically provides a variable gain factor during operation (adaptive controller).

A condition for the operation of the adaptive controller is that the exit side thickness gauge provides the same curve as the entry side thickness gauge, shifted in time and with a different amplitude level, though. If this is not the case, caused by unround rolls, for example, the adaptive controller is ineffective.

Picture 13) Block Diagram of feedforward control:
Constant Volume Control (Mass Flow)

The constant volume control is an additional control that is applied in combination with the roll gap or position control. The constant volume control needs the online measurement signal of the entry side strip thickness gauge and the current entry and exit side strip speed.

Formulation for the constant volume control:

Entry strip volume = exit strip volume

The strip volume is defined by:

Thickness \times Width \times Length

Since the width remains unchanged in the cold rolling process, the following equation results:

Entry thickness \times entry length = Exit thickness \times exit length

By standardizing the number of measured pulses per unit of time, the entry and exit side strip speeds are obtained. The update rate depends on the preset distance. The synchronization between entry and exit side is particularly important for the detection of the strip speeds. Both speeds must be measured at absolutely the same time.

Entry thickness \times entry speed = Exit thickness \times exit speed

The exit side thickness is the required result. Accordingly resolved, we obtain as a control signal of the constant volume control:

\[ \text{Entry speed} \times \frac{\text{Exit thickness}}{\text{Exit speed}} = \text{Delta s} \]

Theoretically, no exit side strip thickness gauge is necessary to achieve the nominal size, assuming that all measurement values (speeds and entry thickness) measure exactly, but the exit side thickness gauge is usually applied for control and the constant volume control is combined with feedback control.

The constant volume control reacts to speed changes and entry side thickness variations. It is the only type of control where speed changes will not result in thickness variations. Even extreme entry side thickness deviations are controlled without problems.

A condition for a properly working constant volume control is a faultless and highly dynamic detection of the speeds which are scanned simultaneously.

Incremental sensors, mounted on the deflector rolls or specific (nonslip) measurement wheels, with a resolution of \( \geq 5000 \) incr./revolution, or laser speedmeters with a similar resolution and accuracy are recommended here. The resolution is quadrupled \( \geq 20000 \) internally. Typical distances for the speed measurement are a few centimeters, requiring measurement intervals within a millisecond range, in particular for mills with high strip speeds \( >15 \text{ m/s} \). The constant volume control works highly dynamically. Numerous plausibility controls offer practical protective measures so that measurement errors will not lead to strip breaks.

The above features make the constant volume control the ideal additional control for the roll gap or position control. In combination with the feedforward and feedback control, excellent thickness tolerances will be achieved if the optimum technical conditions for the mill are maintained. Scrap can be reduced considerably since the nominal size is achieved after a few meters \( (2 \times \text{distance roll gap} - \text{thickness gauge}) \) and speed change effects are minimized.
Figure 14) Thickness deviation - Volume control:

Picture 15) Block Diagram of constant volume control:

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**General chart Massflow control**

### Basic control loop:
- Position control
- Gap control

### Additional control loop:
- Massflow control

**Parameters:**
- \( V_0 \): Ingoging mill speed
- \( V_1 \): Outgoing mill speed
- \( h_0 \): Ingoging Thickness
- \( h_1 \): Outgoing Thickness
- \( F_{w0} \): Sum Reference
- \( C_m \): Material valuation \((F_{w0} + h_0)\)
- \( C_g \): Mill constant \((F_{w0} + \Delta h)\)
- \( \Delta h_0 \): Ingoging thickness deviation

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Skin-Pass Control (Elongation and Reduction)

The skin-pass control is an additional control that is applied in combination with the roll force, roll gap or position control. The entry and exit speed is needed for the detection of the actual strip elongation (relative strip elongation).

The accurate speed measurement is critical for the skin-pass control. Typical nominal skin-pass values are within a range of 0,3 % to 8,0 %. To control a nominal preset of 0,3 %, the accuracy of the speed measurement must be < 0,1 %. Incremental sensors, mounted on the deflector rolls or specific (nonslip) measurement wheels, with a resolution of >=5000 pulses/revolution, or laser speedmeters with a similar resolution and accuracy are recommended here.

The skin-pass measurement is related to the length. The ratio between a covered distance in the inlet and a simultaneously measured distance in the outlet is formed as follows:

\[
\text{Elongation} [\%] = \frac{(\text{Exit pulses} - \text{entry pulses}) \times 100}{\text{entry pulses}}
\]

If the reduction is to be defined instead of the elongation, the following equation applies:

\[
\text{Reduction} [\%] = \frac{(\text{Exit pulses} - \text{entry pulses}) \times 100}{\text{exit pulses}}
\]

By standardizing the number of measured pulses per unit of time, the entry and exit side strip speeds are obtained. The update rate depends on the preset distance. The synchronization between entry and exit side is particularly important for the detection of the strip speeds. Both speeds must be measured at absolutely the same time.

The skin-pass control compares the result of the measurement with the nominal preset, sending calculated control commands to the roll force, roll gap or position control if adjustable threshold values have been exceeded. These control commands cause a change of the roll gap (drive and operator side are moved in parallel), leading to a different elongation, reduction resp. After the control command has been given, a control pause time is waited before a new measurement. The gain factor of the control commands is adjustable and can be varied online in dependence of the material attributes (such as hardness).

Extensive plausibility controls are provided to suppress errors due to incorrect measurements during the length measurement.

Nominal elongation or reduction values can be preset.

The actual elongation value, reduction value resp., the nominal value and the deviation between actual and nominal value are indicated.

Optional interfaces for nominal preset via pass schedule software or actual data recording via VGraph SPC software are possible.

Figure 16) Block Diagram of skin-pass control: