# Advanced semi-automatic straightening technology

**Using the latest technology provides strategic advantages of mass customization that make it easier for manufacturers to make wire products at the increasingly high levels of quality demanded today by customers.**

**By Marcus Paech**

### Motivation

From a global perspective, companies compete with similar constraints that have identical variables. However, there can be local differences that affect variables, such as labor, energy and raw material costs. Differentiation strategies are available that, based on advanced product manufacturing methods, can help offset such disadvantages. Some keys of these advanced manufacturing techniques include: the availability of process and setup data before the process begins; accurate, fast and reliable verification of setup data; and the ability to produce customer-specific products in small batches based on the rules of mass production (mass customization).

### The roll straightening process

Excellent process planning and optimization, intelligent, flexible machinery technology as well as advanced information and communications technology are absolutely essential for the design of these production processes. An analysis of the production process in the wire industry shows that the roll-straightening process is one of the key production steps. In wire production and processing, the straightening process defines the engineering and business variables which determine success or failure. If, for example, finished products do not conform to geometric specifications as defined in standards such as EN 10218-2, it can take more time, material and labor to produce a product, making production inefficient. In addition to conformance to geometric specifications, there is increasing interest in other information and characteristics which are very important for the downstream production process. In this context, the wire straightening operation must evolve into a manufacturing process which makes it possible to continuously identify the properties of the process material and which is also capable of constantly maintaining specific

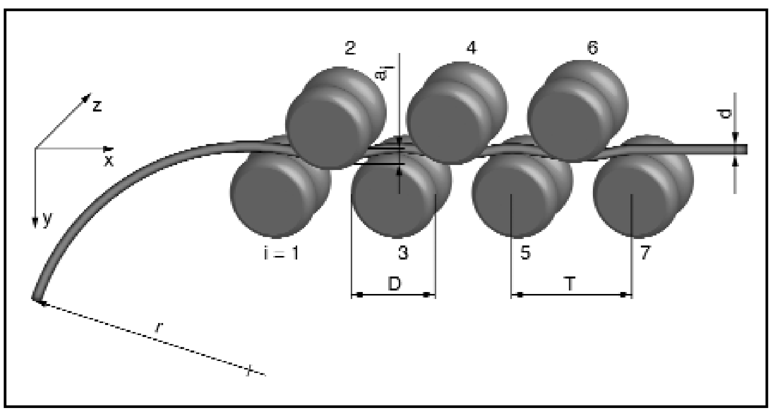


**Fig. 1. Schematic diagram of roll straightening process showing key selected variables.**


**Photo 1. An example of advanced semi-automatic straightening technology.**

## Editor's Note

*Due to space limitations, it was not possible to present all the text and figures in this paper. The complete original paper can be found at wirenet.org by clicking on "Wire Journal Extra" and then "Paech."*

material characteristics.

Given the level of complexity, it is difficult to understand why the acceptance and utilization of semi-automatic straightening technology in the wire industry has not kept pace with the available options. An analysis of insular solutions in practical applications[1,2] reveals that, from the list of characteristics above, only verification of setup data has actually been implemented. The remaining characteristics are not used in combination with semi-automatic straightening technology in practical application. Potential suppliers as well as the users of semi-automatic straightening equipment are both to blame for this situation. On the user side, management is focused exclusively on short-term profitability. It lacks creativity and does not have the courage to take risks. Despite the associated competitive disadvantages, managers are unwilling to invest in innovation which is nothing other than creativity that has become reality[3]. The level of investment is insufficient, because the persons making the decisions are reluctant to spend what they perceive to be large sums. Usually no attempt is made to weigh up the investment costs against the engineering and business benefits. Suppliers can help raise the level of investment if they offer advanced semi-automatic straightening technology which is cost-effective and suitable for the application and if they find ways of communicating the advantages of the technology in a way that the users can readily understand. See Photo 1. In taking up the challenge, a new approach was used rather than relying on existing strategies.

Straightening is primarily needed to modify or remove curvature in process material. Curvature is induced by mechanical and thermal effects, and it can be desirable or undesirable. As a secondary effect, the straightening process affects the mechanical properties of the process material such as elongation limit $R_p$, tensile strength $R_m$, modulus of elasticity E and residual stress potential $W_E$. The shape curve of a process material, which is not exposed to external forces and moments, is based on the equilibrium of internal forces and moments.

A straightener, which has straightening rolls arranged in two alternating rows, can effectively modify or eliminate one dimensional curvature[4]. The positioning of the adjustable straightening rolls $a_i$ causes alternate elastic/plastic deformation which forms the basis for changes to the geometric and mechanical properties of the process material. Fig. 1 shows selected process material and straightener variables for a process which is used to straighten a wire with diameter d.

Every straightener has a specific straightening range Δ, which is determined by the spacing T (the distance between straightening rolls) and the diameter of the straightening rolls D (Fig. 1).

Depending on these variables, the straightening range Δ has a minimum and maximum limit and a maximum cross-sectional dimension of the process material which can be straightened. The minimum and maximum wire diameter $d_{min}$ and $d_{max}$ are relevant parameters for round wire and are shown in Eq. (1) as follows:

$$d_{min} \leq \Delta \leq d_{max} \quad \textbf{Eq. (1)}$$

The number of rolls which are needed in a straightener depends on the elongation limit $R_p$ and the range of the radius of curvature Δ r using the maximum ($r_{max}$) and minimum radius of curvature ($r_{min}$) as shown in Eq. (2).

$$\Delta r = \left| r_{max} - r_{min} \right| \quad \textbf{Eq. (2)}$$

The rule of thumb is that to achieve good finished product quality, the number of rolls needed increases as the elongation limit and the range of the radius of curvature increase.

Fuzzy logic is used to determine the number of rolls n. Knowledge based on empirical data can be formulated in verbal rules for input into a fuzzy logic system. The knowledge base consists of linguistic terms (membership functions) for the input and output variables, the rule base and the inference and defuzzification functions[5]. The rule base creates a link between the range of the curvature of radius Δr and the elongation limit $R_p$ as the input variables and the number of rolls n as the output variable.

The use of an appropriate inference mechanism and a specific defuzzification method finally produces a specific transformation pattern. Thus a set of sharply defined input variables can be used to generate a sharply defined output variable. Table 1 shows some discrete values for the number of rolls n, which were derived from the input variables elongation limit $R_p$ and range of the radius of curvature Δr.

## Deformation power requirements

Power is needed to deform process materials using straightening rolls. The amount of power required depends on key variables of the straightening device and the process material as well as the type and speed of roller adjustment.

Translation or rotation that is converted to translation can be used to make the best individual roll adjustment. Adjustment screws or spindles, which act as gear units with good self-locking and convert torque $M_{iG}$ into adjustment force $F_{iA}$, are

| Range of initial radius of curvature Δr [mm] | Elongation limit $R_p$ [MPa] | No. of straightening rolls n [-] |
|---|---|---|
| 0 | 1000 | 5 |
| 60 | 1000 | 7 |
| 100 | 1000 | 9 |
| 100 | 2000 | 11 |
| 160 | 2000 | 13 |

**Table 1. Values for the number of straightening rolls n based on fuzzy logic.**

popular solutions. The variables that apply to these gear units are thread flank diameter $d_{iF}$, mean helix angle $\alpha_{im}$, and friction angle $\rho'_i$. The angular velocity $\varpi_{iG}$ and respectively the spindle speed $n_{iG}$ can be used in Eq. (3) to calculate the minimum power $P_i$ which is required to adjust roll i.

$$P_i = M_{iG} \cdot \omega_{iG} = F_{iA} \cdot \tan(\alpha_{im} + \rho'_i) \cdot \frac{d_{iF}}{2} \cdot \frac{\pi \cdot n_{iG}}{30} \quad \textbf{Eq. (3)}$$

The adjustment force $F_{iA}$ results from the deformation of the process material in the area which is affected by straightening roll i. It is equal to the amount of straightening force $|F_{iR}|$ Eq. (4), which is applied at the point where process material contacts the straightening roll in correlation with reaction forces.

$$F_{iA} = |F_{iR}| \quad \textbf{Eq. (4)}$$

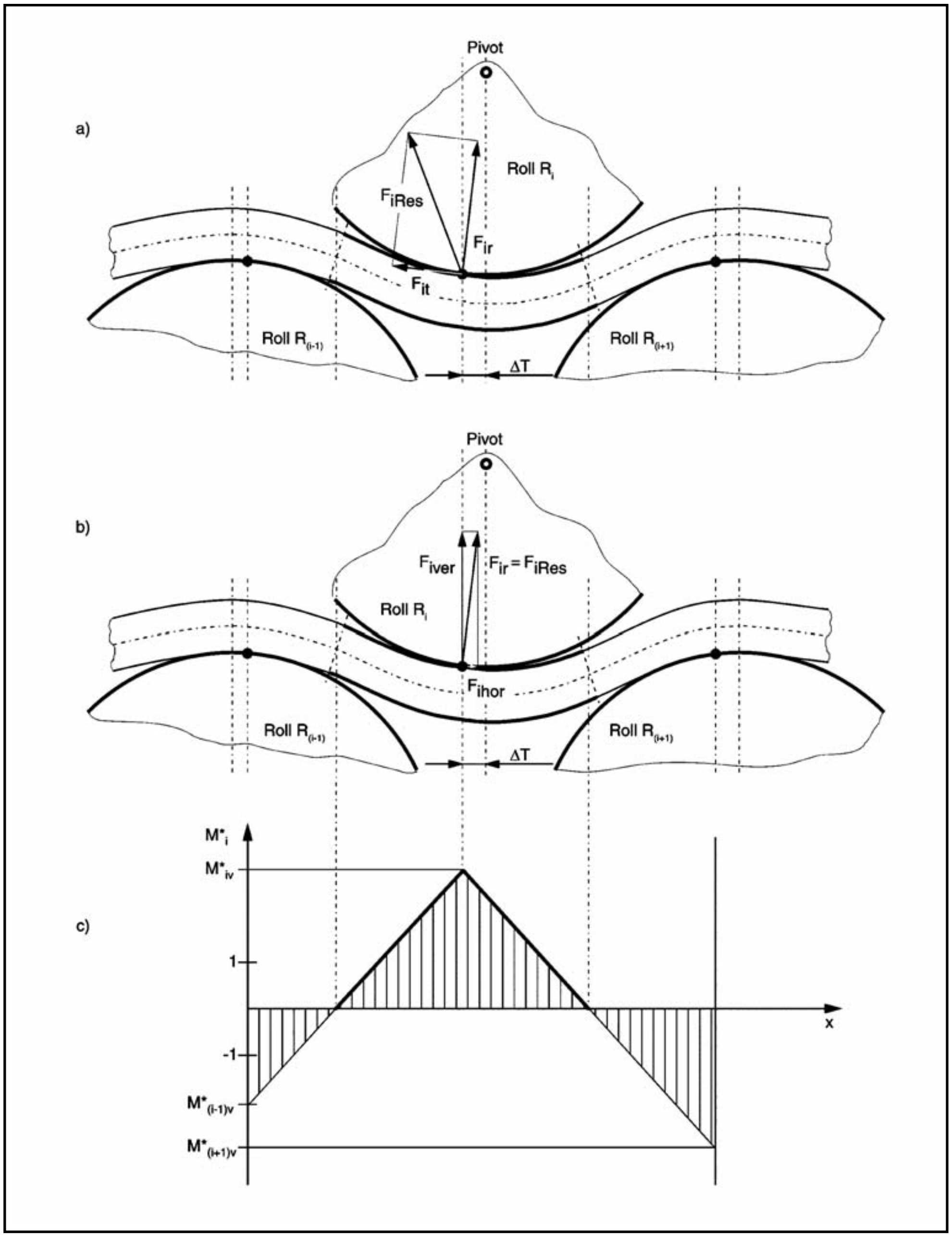


**Fig. 2. Reaction forces $F_{ir}$ and $F_{it}$, resulting straightening force $F_{iRes}$, components $F_{iver}$ and $F_{ihor}$ and the graph of the non-dimensional bending moment $M^*_i = f(x)$.**

Analysis of the quasi-static case allows one to ignore external forces and the tangential reaction force $F_{it}$. The radial reaction force at the straightening roll is equal to the resulting straightening force (Fig. 2 a).

If one ignores the spacing which has changed by $\Delta T$, then the straightening force $F_{iR}$ is only made up of the vertical component of the resulting straightening force $F_{iver}$ (Eq. 5, Fig. 2 b).

$$F_{iR} = F_{iver} \qquad \textbf{Eq. (5)}$$

Calculation of the amount of non-dimensional straightening force $|F^*_{iR}|$ using Eq. 6 is based on equilibrium analysis which includes the bending moments at the rolls (Fig. 2 c) and the spacing.

$$|F^*_{iR}| = |M^*_{(i-1)v}| + |2 \cdot M^*_{iv}| + |M^*_{(i+1)v}| \qquad \textbf{Eq. (6)}$$

The use of non-dimensional values (indicated by an asterisk) simplifies the calculation[6]. Eq. 7 is used to calculate the adjustment force $F_{iA}$ (Eq. 4) or the actual straightening force $|F_{iR}|$.

$$|F_{iR}| = \left(\frac{R_p \cdot \pi \cdot d^3}{16 \cdot T}\right) \cdot \left(|M^*_{(i-1)v}| + |2 \cdot M^*_{iv}| + |M^*_{(i+1)v}|\right)$$

**Eq. (7)**

The analysis presented above shows that calculation of the bending moments $M_{(i-1)v}$, $M_{iv}$ and $M_{(i+1)v}$ is needed to determine the power which is required to achieve deformation. Simulation of the straightening process[6] can be run to generate numeric bending moment/curvature graphs. The analysis uses iteration to calculate the curve for bending moment $M^* = f(x)$ (Fig. 2 c), curvature $K^* = f(x)$ and the bending line of the process material $y = f(x)$ for a given roll adjustment. With the bending moment curve also the non-dimensional values for the bending moments for calculating the amount of power required are known.

## Concepts

The section on motivation described important characteristics of an advanced production process. Conventional straighteners do not possess these characteristics. The straightening rolls, which are the tools on straighteners, can be adjusted, but the adjustment is not defined and reproducible, because the equipment which would be required to do so such as instrumentation is lacking. Tools such as wrenches or screwdrivers are used to move the adjustment screws until the process material has the right curvature at the outlet or other quality criteria are met. Conventional straighteners have a static design. There is no way for the user to expand the application horizon to handle alternative cross-sectional geometries or materials. As a result, they are not suitable for tomorrow's advanced manufacturing scenarios.

Instead of using simple tools to adjust straightening rolls, advanced semi-automatic straighteners are equipped with actuators which have a motor and a gear unit. These actuators work in conjunction with automation equipment and software to determine and set the target position of the straightening rolls based on the desired finished product quality. This type of design leads to: guaranteed high actuating forces; remote operation; minimized operator error; minimized time, human resources and volume of process material needed to achieve the desired product quality; and precise, automatic setting at specific tool positions which is appropriate for a particular process material and tool geometry.

## Subsystem types

The conceptual design of the advanced semi-automated straightener contains three sub-systems. The mechanical, electrical and software subsystems (see Fig. 3) are based on lean design principles, means that the component count is kept to a minimum.

*Mechanical subsystem.* The servomotor (M), planetary gear (G), spindle adjustment mechanism and slide as well as the roll axis and straightening rolls are located in the mechanical system power train (Fig. 4). The combination of all of these elements on a single module is the revolutionary new feature of this design. Because the system is modular, customer-specific versions of the straighteners can be produced quickly and efficiently while still adhering to the laws of mass production and the applicable pricing guidelines (mass customization = mass

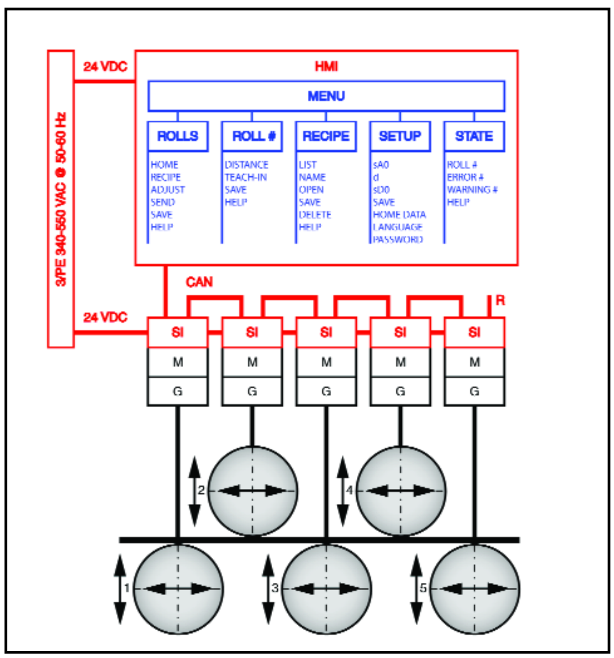


**Fig. 3. Conceptual design of advanced semi-automatic straightening technology with mechanical, electrical and software subsystems.**

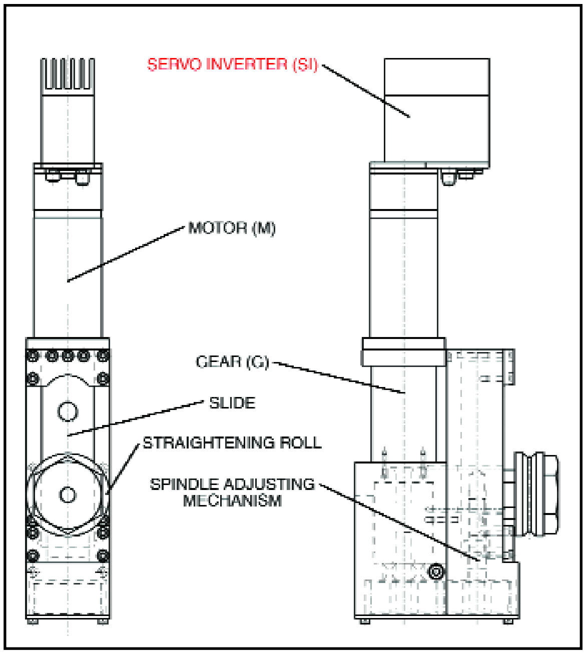


**Fig. 4. Modular mechanical subsystem.**

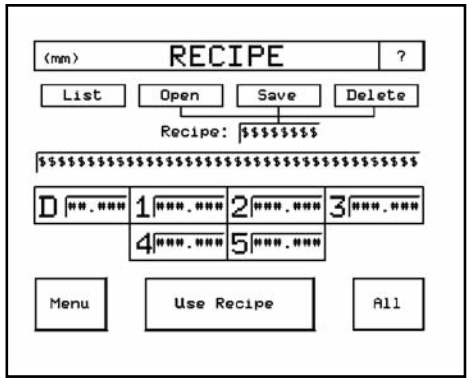


**Fig. 5. Menu for the synchronous positioning of rolls.**

production + customization[7]).

Straighteners with a specific number of straightening rolls n and specific spacing T can be produced cost-efficiently at short notice on customer request. Advanced straightening technology uses process simulation[6] to determine optimal spacing T and maximum straightening range Δ see (Eq. 1). Optimization of spacing T is based on the level of finished product quality that the customer wants as well as the material characteristics.

Modular design also offers the advantage that modules with actuators can be paired with modules that have non-adjustable straightening rolls. Customers can maintain the functional profile at a lower investment cost. From the user's point of view, advanced straightening technology based on mass customization offers the advantage that products can be made in small lots using a mass customization process. This approach is feasible if the straightening equipment offers variable spacing T. Users can adjust roll spacing on site (see Fig. 3) to create perfect conditions for handling special materials or cross-sections (wire, tube, etc.). Theoretical and practical results demonstrate the significant influence which spacing T has on finished product quality and the required roll adjustment accuracy[8].

With the exception of the motor and the gear unit, the elements in the mechanical subsystem are mounted on a high-precision base which can be subdivided along the axis of the roll shaft. This ensures high power density. The calculation used to determine the power needed to deform the process material and to position the rolls is based the applicable rules. The initial version of the straightener is suitable for round wire in the 5-15 mm diameter range. It can also be used for elastic/plastic deformation of profile wire, flat wire or tubing.

Pretension on the spindle adjustment mechanism can be set to increase positioning accuracy. There are two holes in the slide to hold at least one roll shaft. The roll shafts and straightening rolls can be customized to meet customer needs. Series FT roll shafts, for example, can be a good choice if there is a need to quickly change straightening rolls without tools or to use long-wearing straightening rolls which feature a special design and materials such as ceramics or hard alloy.

*Electrical subsystem.* Conventional positioning systems consist of an industrial control unit, inverters and sensors which are embedded into hierarchical or distributed control systems. Serial communication and power cabling is usually connected to the control unit using a star topology. These discrete designs require elaborate cabling design and significant implementation effort which can easily become quite costly.

An alternative electrical system, which contains nothing more than servo converters and a touch-screen HMI (human machine interface), has been developed for advanced straightening technology. A servo converter, which communicates with the higher-level HMI via the CAN data bus, is allocated to each module (see Fig. 4). Up to 32 modules can be run in a cluster, and energy management has been designed to support synchronous positioning of the rolls on all 32 modules.

The modular design and topology support genuine plug and play functionality. An actuator and servo converter can be swapped without any additional effort because all communication settings and initialization of new components are performed in the factory. The system can be regenerated by changing components without any loss of information.

No proximity switches or sensors are used to detect end of travel or for travel to the home position on advanced semi-automatic straightening equipment, because intelligent routines in the software sub-system reliably perform these functions. Elimination of the need for a higher level controller (e.g. a PLC or computer) helps keep the component count down. The HMI, software and the servo converters provide an alternative solution.

*Software subsystem.* Software implemented on the HMI manages communications with the module inverter or the servo inverters if more than one module is used. The software subsystem contains all of the routines that are needed to support advanced semi-automatic straightening technology. Following are the routines provided for a module (see Fig. 3):• parameterization (module specific zero line, wire diameter); calculate the wire-specific zero line; calculate the absolute roll position; move to home position without sensors or proximity switches; adjust in inching mode (teach-in); display set point data records; select, modify, save, delete or send set point data record (recipe management); adjust to set point defined in a data record; show actual adjustment position; adjustment limit; spindle play compensation; overload protection; status display; access management (password); change language; and help

Fig. 5 shows the menu for a routine realizing a synchronous positioning of the straightening rolls (RECIPE). It uses so-called set point records or recipes. They contain the adjustment position $_{ai}$ and wire diameter d for every module. The user can select, create, edit or delete records on the HMI at any time. Once a record has been selected, the next step is to send setup information $a_i$, which is stored in the record, to the inverters. This allows, for example, to adjust the zero line considering the actual wire diameter, a quick opening or an accurate roll adjustment in seconds.

The roll adjustments, which are needed to produce straight process material, are based on simulation of the straightening process[6] which is run using SimDATA software[9]. SimDATA is a simple program which uses binary coded equipment libraries that contain information about the roll positions which are needed to achieve a defined finished product quality.

The availability of SimDATA fulfills another advanced production criterion, because setup data for the advanced semi-automatic straightening equipment is available before the process commences. A version of the software can be supplied which can for example be used to calculate setup data in ad-vance for production of process material with defined curvature.

## Summary

The power requirements for the process material deformation process are based on the working principle and the main characteristics of the straightening process. A simulation program, which uses a virtual model of the straightening process, is available to support the assessment of the power requirements. Simulation in turn is based on a theoretical model of alternate elastic/plastic deformation and the relationship between bending moment and curvature during bending operations. This article describes advanced semi-automatic straightening technology. The equipment consists of mechanical, electrical and software subsystems, and it meets advanced manufacturing process criteria. Advanced straightening technology features a modular design, minimal component count, a user-friendly HMI and the availability of process and setup data prior to the start of the process. The flexibility of the design and the ability to manipulate the number and spacing of the rolls, which are the main variables, produce a system which can be used to make customer specific products in small lot sizes. Users benefit from the strategic advantages of mass customization, which enables producers to supply ex-actly the product and quality which their customers are looking for. Photo 1 shows the mechanical subsystem and one electrical subsystem component on the CS EASY 5-15.0 LE version.

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