sciendo

Power Electronics and Drives
Volume 9(44), 2024 DOI: 10.2478/pead-2024-0030

Power Electronics and Drives

Shearing Work Analysis and Control Design of Rotary Shears in Material Processing Lines

Research paper

Viktor Šlapák*, František Ďurovský, Karol Kyslan, Pavol Smoleň

Department of Electrical Engineering and Mechatronics, Technical University of Košice, Košice, Slovakia

Received: 06 April 2024; Accepted: 13 September 2024

Abstract: Rotary shears are common part of the material processing lines (MPL). During the operation, these shears are loaded with impact cutting torque, which takes only short time but reaches values compared to motor-rated torque. Therefore, it is a technical challenge to ensure the speed stability during the cut. The presented paper deals with the analysis of the rotary shears' operation and material cutting process from the control point of view and presents a cutting torque compensation possibility. Three types of speed controllers without and with cutting torque compensation are compared.

Keywords: *rotary shears • motion control • industrial drives • torque compensation*

1. Introduction

Industrial lines for material processing (material processing lines [MPL]) often include devices for the material cutting to required shape and dimensions. If material cross cutting is required, one of the flying cutters or shears is commonly used. The outputs of MPL with a cutter are plates of a defined length.

In general, the input section (IS) of MPL with a flying cutter consists of an unwinder and possibly a leveller (Figure 1). The unwinder unwinds the material from the coil and the leveller levels the material to achieve a flat surface (Magura et al., 2014). Such IS assembly is common mainly in a steel strip cutting.

Next, the MPL employs the loop pit and feed rolls. The loop pit separates the line IS from the technological processing section (PS), where the strip is cut. As a result, fluctuations in speed within the IS do not affect the PS and vice versa. At the same time, the loop pit serves as the material accumulator for the shears. For processing wooden boards, pressed or glued, the material is continuously supplied to the cutting part directly from the press without using the loop pit.

The feed rolls before the shears pull the strip out of the loop pit and feeds it into the shears. The length of the material strip can be measured directly by the position sensor placed on feed rolls or by the wheel that is installed between the feed rolls and the shears. Conveyors, positioned behind the shears, handle the removal of cut material, ensuring its orderly stacking and subsequent packaging.

A flying cutting provides the material splitting at full line speed (Cinquemani and Giberti, 2015). Depending on the type of processed materials, the following types of cutting technologies are available (Ďurovský et al., 2023):

- *Flying saw* is used for a thick material, which cannot be split by chopping, e.g. solid or glued pressed wooden boards and plasterboard, etc. A special case is the splitting of steel slabs at the end of continuous steel

---

* Email: viktor.slapak@tuke.sk

casting. In that case, the cutting is done by a plasma torch instead of the saw. The splitting mechanism is usually placed on a carriage, which waits in the starting position until the material strip reaches a length close to the desired format (Zang and Song, 2015). Before the splitting, the carriage accelerates to the speed synchronised with the strip. Next, the splitting mechanism (saw, torch) traverses the full width of the strip until the material is entirely separated. Once the cut is finished, the carriage returns to its initial position and awaits the next cutting operation.

- *Flying shears* or *flying knives* are used to split thinner materials, which can be processed by chopping (Bi et al., 2020). The splitting mechanism is positioned on a carriage, which is similar to the arrangement of a flying saw. The difference is only in the manner of material splitting. The shears placed on a swinging arm (Fetyko et al., 2008) can also be included in this category.
- *Rotary shears* or *rotary knives* have a fixed support. The knives are placed on the circumference of one or two drums rotating against each other. To cut softer and thinner materials, the knives can be directly positioned around the circumference of the drum. For firm or thick materials, the set-up is adjusted to ensure that the knives are consistently perpendicular to the strip (see Figure 2).

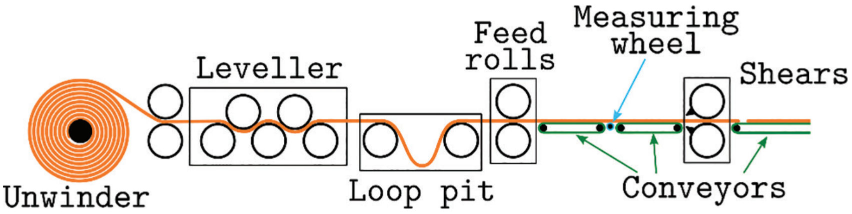


Figure 1. An example of MPL—steel sheet cutting. MPL, material processing lines.

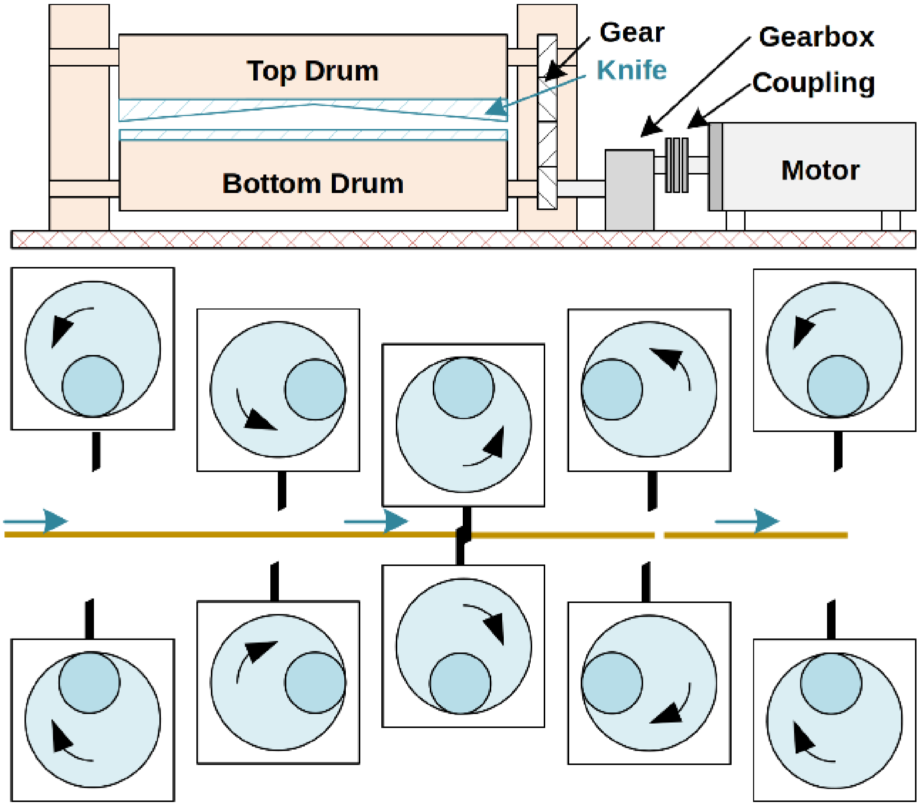


Figure 2. An example of a rotary knife arrangement.

Only few authors address the control of flying shears in literature. In an earlier work (Peric and Petrovic, 1990), the authors focused on a position control with torque minimisation, implemented in a microcomputer. Madhivanan and Narayanan (2012) used an FPGA-based system dealing with generalised speed and torque referencing system for the control of flying shears. Wang et al. (2017) investigated an energy optimisation of position control of carriage with a saw. A servo controller with electronic cam was implemented to realise the function of moving for flying shears' mechanism.

In other works, programmable logic controller (PLC)-based commercial control systems were employed. Solomon and Gaiceanu (2021) applied the SIMOTION control system. Karandaev et al. (2020) used a combination of PLC and a special microcontroller to improve the position control of analogue-controlled DC power converter. Ng et al. (2017) presented a bar shearing using an ABB drive with direct torque control and a superior PLC.

Manuals for commercial shears control software, e.g. Siemens manuals (Siemens AG, 2014), can provide a good insight into shears' control in industrial environment. In older systems by Siemens, a technology control of shears is implemented either in special technology card FM 458 inserted into the PLC (Siemens AG, 2011) or by a technology card T400 (Siemens AG, 2001) inserted directly into the SIMOVERT Master Drive (Siemens AG, 2004) or SIMOREG DC Master (Siemens AG, 2007) power converters. The most recent inverters from the SINAMICS family (Siemens AG, 2017a) use SW modules based on DCC (Siemens AG, 2015) implemented either in the CU320 inverter control unit or in the SIMOTION (Siemens) control system (Siemens AG, 2017b). Solutions for flying or rotary shears are also offered by other manufacturers, but unfortunately this is often an internal know-how that is not commonly published and remains inaccessible to third parties.

However, the available literature lacks an analysis of required cutting work and its effect on the shears, although it plays a significant role in shears' control. Therefore, the presented paper objective is to analyse cutting work and describe a solution, how to provide the energy to cover it. The second objective follows the conditions, which must be met to achieve a high-cutting accuracy. Both objectives are presented using case study with two drum rotary shears and its control structure.

In Section 2, the paper describes the principle of rotary shears' operation. An analysis of cutting forces and energy requirements is presented in Sections 3 and 4. Section 5 presents a suitable control algorithm using a cutting torque compensation. The described sections represent the theoretical background of shears' operation. Next, in Section 6, a problem definition is described in detail using measurements on real MPL. In the final section, different types of speed controllers without and with torque compensation are compared during the cutting period by simulations, followed by implementation challenges that need to be addressed in practice.

2. Principle of Rotary Shears' Operation

The shears are usually driven by an electric motor with the gearbox, as it is shown in Figure 2. The shearing mechanism moves along a circular path, which keeps the knives perpendicular to the strip. The radius of this circular track is referenced as the *fictitious radius* and the circumference of the track as the *fictitious circumference*. The length of the cut material is denoted as the *cut format* or *format* for short. If the circumferential movement distance of the shears is equal to the movement distance of the material strip, then the shears' circumferential speed is the same as the strip speed, i.e. the *synchronous speed*.

If the cut format is longer than the fictitious circumference, the shears wait for the material in parking position (PP) (Figure 2, on the left side). At the calculated instant, the shears accelerate from the PP until the synchronous speed is reached. In synchronous speed, the cut is performed (Figure 2, in the middle). After the cut, the shears slow down or even stop in the PP (Figure 2, on the right side).

If the cut format is shorter than the fictitious circumference, the shears do not decelerate after the cut, but accelerate to a higher speed and then slow down back to the synchronous speed. The shears will not stop in PP in this case.

In general, one cutting cycle (acceleration, cutting, braking) is completed in less than a second. This puts considerable demands on the dynamic capabilities of the drive system. Therefore, in the case of shears with a large inertia and when the shears are driven from a frequency converter, the additional capacity is added to the DC-link. Dynamic energy is thus absorbed/stored in the DC-link and does not flow to/from the power network.

2.1. Shears' important positions and areas

In the shears' control, several important points and areas must be defined (Figure 3) (Siemens AG, 2015):

- Reference point (RP)—The shears' positioning is usually referenced to the lower position of the knives. The angular coordinate of the RP is 0° in this paper.
- Synchronous range (SR)—The SR is the area located around the RP, where the shears have the same circumferential speed as the strip. The area is bounded by two points: start of synchronous range (SSR) and end of synchronous range (ESR).
- Formatting range (FR)—In the FR, the shears' speed may not be equal to the strip speed.
- Parking position (PP)—In this position, shears wait for the material between cuts in the case of long formats. The PP location is set according to shears' dynamics to allow the shears to brake between the ESR and the PP and then accelerate to the synchronous speed between the PP and the SSR. Usually, the PP is located at the inflection point (180°). However, if the formats are very long, it is possible to reverse move the shears after stopping. In that case, the PP may be placed sooner than in 180° after cut. The shears will thus accelerate and brake on a longer track and will not need such a high dynamic torque as if they were to accelerate from or slow down to 180°. This approach is especially advantageous for very high strip speeds.

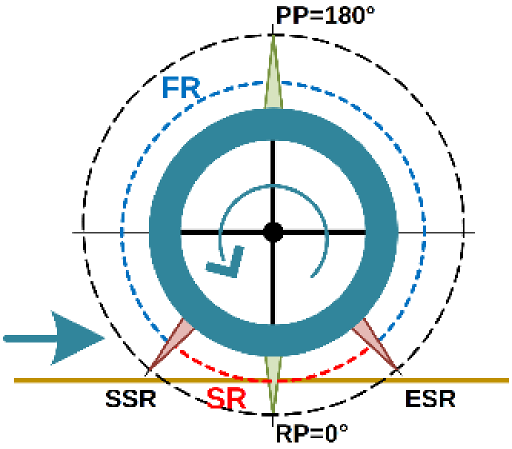


Figure 3. Important areas and significant points at cutting. ESR, end of synchronous range; FR, formatting range; PP, parking position; RP, reference point; SR, synchronous range; SSR, start of synchronous range.

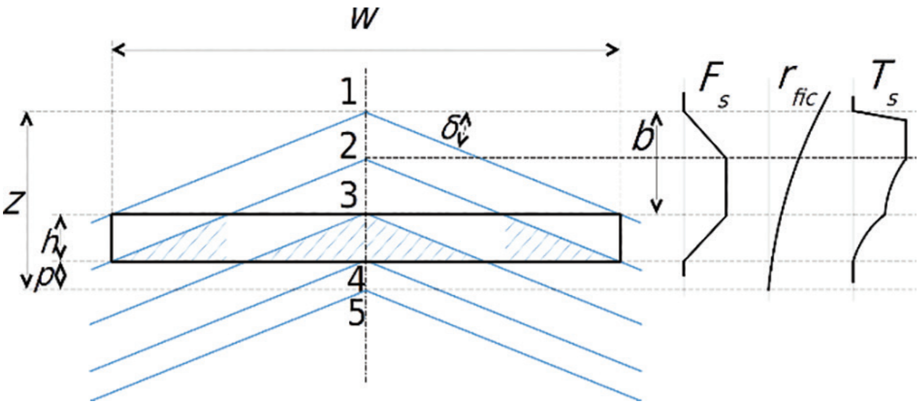


Figure 4. The design of shears' blades and the cutting process. Legend: z—cutting stroke, h, w—thick and width of cut material, p—shear overlap, δ—shears' blades inclination, b—path for calculation of shearing work, F_s—shearing force, r_{fic}—arm on which the shearing force acts, T_s—shearing torque.

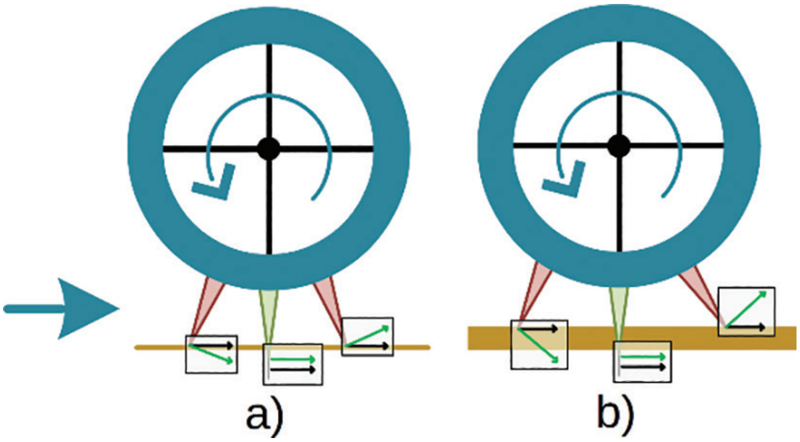


Figure 5. Differences between cutting thin and thick materials—(a) thin material and (b) thick material.

The shears' speed in the SR depends also on the shears' design and the thickness of cut material. The shears discussed in the paper have blades arranged in V shape (Figure 4). The total stroke of the knives (cutting stroke) is z and the overlap is p. The thickness of the cut material is denoted as h. The mentioned parameters affect the circumferential speed required at first contact of knives with the material (the so-called cut-into instant).

If the cut material is thin and the shears' overlap in the RP is small, the cut will occur near the RP (Figure 5a). In this area, the projection of the shears' circumferential speed in the direction of strip movement is also close (or equal) to the strip speed. This means that the cutting will be performed without unwanted side effects. However, if the material is thicker and/or the shears' overlap is increased, the cut-into instant will happen sooner (Figure 5b). If the shears' circumferential speed equals the strip speed, the projection of the shears' circumferential speed in the direction of strip movement will be less than the strip speed. In this and every other case, when shears' circumferential speed during cutting becomes lower than the strip speed, the strip starts to push to the shears' knives. As the feed rolls will not slow down, the material may form a bubble before the shears. If the separate measuring wheel is used, this can cause an inaccurate measurement of material length or even complete losing of the position information. In the worst case, losing the position information, which act as the reference for the shears, may stop the shears during cutting and as the feed rolls will continue to feed the material, it can accumulate between feed rolls and shears, thus damaging itself and possibly the mechanics as well.

The cutting work, during the material splitting, needs to be covered by kinetic energy of the shears and/or by torque loop of the drive. If sufficient energy is not available or provided at the right moment, the shears may suddenly slow down, resulting in the same consequences as described earlier.

If too much energy is provided to shears during cutting, the shears will move faster than the strip during the cut and they will drag the strip. Because the shears' speed reference is derived from the strip speed, accelerating the strip would also increase the speed of the shears, causing a positive feedback loop. With each cut, the shears subsequently tear the strip. If the cut occurs at the right moment, the aforementioned phenomenon will not impact the cutting accuracy. However, it may increase the wear of mechanical parts, especially the surface of feed rolls and its gearbox.

After the cut, the shears accelerate to move the blades away from the rest of strip and then slow down to the PP. The ideal shears' speed trajectory, considering all the mentioned aspects, is shown in Figure 6, where an overspeed is used to ensure the proper knife speed projection.

The speed changes described during the cut can last only tens of milliseconds, which puts high demands on the drive system:

- the shear control system must be able to generate the desired shape of the speed reference trajectory,
- the communication channel between the technological controller and the inverter must be sufficiently fast to transfer the speed set point,
- the speed control loop of the power inverter must be able to follow the reference value with high accuracy.

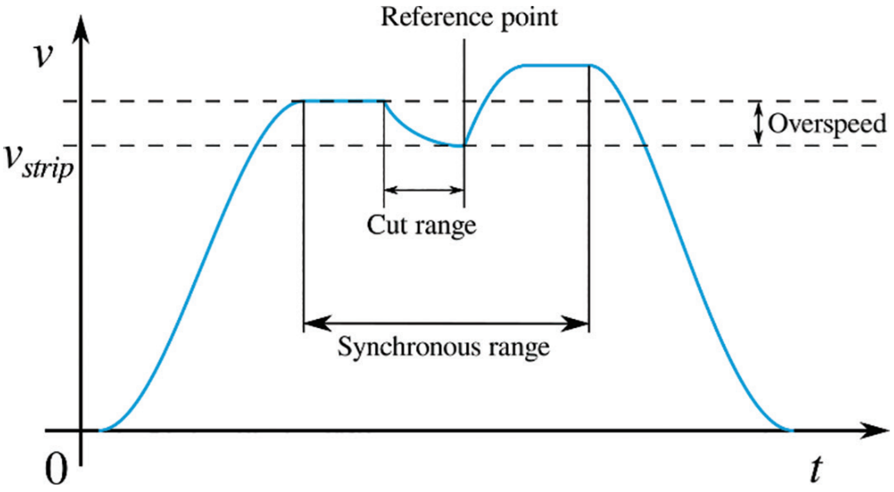


Figure 6. The ideal shears' speed trajectory during cutting.

The determination of cut-into instant depends on the thickness and width of the cut material and on the shears' overlap. As this instant depends solely on geometric dimensions, it is predictable and remains constant during cutting.

2.2. Energy requirements

Flying shears use separate independent drives for positioning and cutting. Positioning is usually done by a drive with less power rating, whereas the cutting itself is performed by a second drive via a flywheel (Fetyko et al., 2008). The energy, which is required to cut the material, is supplied by the kinetic energy of the flywheel. The spinning flywheel is connected to the shearing mechanism through the friction clutch at the appropriate moment, and after the strip is cut, the clutch is disengaged. The speed of the flywheel is approximately constant; therefore, the available kinetic energy for the cutting is also constant at any strip speed. Moreover, since the energy for cutting is supplied by a separate drive, it does not directly affect the cutting accuracy.

The situation is different with the rotary shears, where a single drive handles both tasks. During soft or thin materials cutting, the shearing work is minimal, so the drive is able to cover it either from the shears' kinetic energy or by the reaction of speed controller. However, when cutting thicker materials, the shearing work increases. To cover the increased shearing work, the drive must generate an additional torque during cutting. Otherwise, the cut will cause a decrease in the shear speed, or in the case of low strip speed it may even stop the drive entirely. Although the speed controller attempts to mitigate the speed drop by increasing the motor torque, the distinct dynamics between cutting force and the speed controller causes that the cutting process does not proceed smoothly.

Moreover, the additional torque must be generated by the motor at the correct time and with the appropriate magnitude. If it arrives earlier, the shears will accelerate just before the cut, which will cause inaccurate cut length. If the correction comes later, or is inaccurate, the shears' speed during and immediately after the cut will be significantly different from its reference, which will cause undesired mechanical stress on the shears as well as on the feed rollers. The identification of desired magnitude of additional torque is ambiguous and requires a certain level of the drive adaptivity.

3. Cutting Forces Analysis

To determine the torque value required to cut the material, it is necessary to analyse the forces involved during cutting. The cut can be divided into two phases (Spišák et al., 2019). At the beginning of cut, a plastic deformation occurs (the so-called plastic cut). When the material ability to deform plastically is exhausted, it will tear. The depth of the plastic cut is usually from 10% to 40% of the cut sheet thickness.

The shearing force for shears with an inclined knife is defined as follows:

$$F_s = \frac{h^2}{\tan\delta}\sigma_{Ps}. \tag{1}$$

where σ_{Ps} is the shear strength of material and is defined as:

$$\sigma_{Ps} = (0.7 \text{ to } 0.8)\sigma_{Pt} \ , \tag{2}$$

where σ_{Pt} is the tensile strength of material. For practical calculations, some publications give a modified Eq. (1):

$$F_s = (0.25 \text{ to } 0.5)\frac{h^2}{\tan\delta}\sigma_{Ps} \ . \tag{3}$$

Smaller values in Eq. (3) are used for increased blade inclination and for cutting hard and thin sheets. The wear and dulling of the blades will require an increase in cutting force from 15% to 30%, so the shearing force including the effect of the wear is:

$$F_{s\_\max} = (1.15 \text{ to } 1.3)F_s \ . \tag{4}$$

In the case of V-shaped shears, the force $F_{s\_\max}$ will be doubled.

The region where the shearing force acts is shown by hatching in Figure 4. The knives start to penetrate the material in position 1. In position 2, the ends of the knives pass through the entire thickness of the strip at its ends. Between points 1 and 2, the shearing force increases. At point 2, the force reaches its maximum value $F_{s\_\max}$ that holds until point 3, when the centre of the shears reaches the upper surface of the strip. From point 3 to point 4, the shear force will decrease. Once the strip has been fully cut, the shears proceed to point 5, which represents the bottom dead centre of the shears. The distance between points 4 and 5 is the shears' overlap *p*. For simplification, the shearing work will be calculated with constant shearing force $F_{s\_\max}$ on the path *b* as:

$$A_s = F_{s\_\max} b \tag{5}$$

4. Analysis of the Requirements for the Shear Controller

The shears' control presented in this part uses parameters of real drive and rotary shears manufactured by STAM S.p.A., Ponzano Veneto, Italy. The shears' parameters are presented in Table 1. The shears are able to cut the metal strip with the properties presented in Table 2. In this section, the forces, which act on rotary shears during the cutting and the shearing work analyses, are described.

Table 1. Rotary shears' parameters.

Parameters	Symbol	Unit	Value
Blade inclination	δ	°	1.5
Shears' width	w_{sh}	mm	1,650
Shears' overlap	p	mm	3.19
Path for shearing work calculation	b	mm	14
Shears' fictitious radius	r_{fic}	mm	95
Shears' fictitious circumference	o_{fic}	mm	596.9
Gearbox ratio	j	–	4.2
Shears' overall inertia (motor side)	J_c	kgm^2	5.59
Shears' overall inertia (load side)	J_{cs}	kgm^2	98.59

4.1. Shearing force calculation

The shearing force calculation was made for the worst case, i.e. when the sheet thickness is 3 mm, the strip width is 1,600 mm and the tensile strength of material is 350 Mpa. Shears' strength of material σ_{Ps} according to Eq. (2) is

$$\sigma_{Ps} = 0.8\sigma_{Pt} = 0.8 \cdot 350 \cdot 10^6 \text{ Pa} = 280 \cdot 10^6 \text{ Pa} . \tag{6}$$

The shearing force on one side of shears, according to Eq. (1), is

$$F_{s1} = \frac{h^2}{\tan\delta}\sigma_{Ps} = \frac{0.003^2}{\tan 1.5°} 280 \cdot 10^6 \text{ N} = 96{,}234.92 \text{ N} . \tag{7}$$

The shears are V-shaped. The maximum cutting force, taking into account 20% wear of the blades, is

$$F_{sc\_\max} = 2F_{s1\_\max} = 2 \cdot 1.2 \cdot F_{s1} = 2 \cdot 1.2 \cdot 96{,}234.92 \text{ N} = 230{,}963.81 \text{ N} . \tag{8}$$

Thus, the maximum cutting force F_{sc_max} must be generated by the motor. The corresponding motor torque depends on the radius at which the force acts. The shears are cut into the strip close to the RP; therefore, the arm length varies from approximately 34 mm to 24.6 mm. The precise value depends on the thickness and the width of the strip. The values of shearing torque for the worst case are presented in Table 3, and the rated torque and other parameters of motor, used in the analysis and simulations, are presented in Table 6. The angle is calculated from the RP point counterclockwise.

Table 3 presents the theoretical motor torque required to cut the strip at zero or very low strip speed. At higher strip speeds, the shears move faster and gain higher kinetic energy, which helps partially cover the shearing work. It is also important to note that according to shears' angle at the beginning and at the end of the cut, the shears pass the whole strip profile in a very short time (Table 4), i.e. the load torque of the shears is very high and very short.

Considering the cutting times, it is obvious that the duration of load torque is comparable to the dynamics of the motor torque loop. Moreover, the load torque value is comparable to motor-rated torque. Here, if the motor is driven without the controllers, the load torque would cause an immediate speed drop, which is significant

Table 2. Cut material parameters.

Parameters	Symbol	Unit	Value
Material thickness	h	mm	0.5–3
Material width	w	mm	1,600
Tensile strength of material	σ_{Pt}	MPa	200–350

Table 3. Shears' position and torque during cut.

	Shears' angle (°)	Shears' arm (mm)	Torque on motor side	
			(Nm)	(% of T_R)
Beginning of cut	339	34.045	1,872.2	76.14
End of cut	345	24.588	1,352.1	55

Strip: h = 3 mm, w = 1,600 mm, σ_{Pt} = 350 MPa, p = 3.19 mm.

Table 4. Calculated durations of shears passing the strip during the cut (with a strip thickness of 3 mm and a strip width of 1,600 mm),

Strip speed (m/min)	Duration of load torque (ms)
20	25.5
50	10.147
80	6.365

Table 5. The shears' angular velocity drop during the cut considering freewheeling shears (i.e. without controllers).

Strip speed (m/min)	Shears' angular velocity			
	Steady state (rad/s)	After cut (rad/s)	Difference (rad/s)	Difference (%)
20	14.74	7.63	7.11	48.34
50	36.847	34.021	2.862	7.77
80	58.938	57.180	1.758	2.98

Table 6. Rotary shears' motor parameters

Parameters	Symbol	Unit	Value
Rated power	P_R	kW	190
Rated voltage	V_R	V	400
Rated speed	n_R	rpm	800
Motor inertia	J_{mot}	kgm^2	4.2
Rated current	I_R	A	335
Rated frequency	f_R	Hz	27.2
Rated torque	T_R	Nm	2,328
Maximum torque	$T_{\max}$	Nm	4,250
Rated power factor	$\cos \Phi$	-	0.942
Rated efficiency	η	%	89

especially in low-speed operation when the kinetic energy is low and thus not able to cover the shearing work during the cut. An overview of this eventual speed drop for various strip speeds is presented in Table 5.

4.2. Shears' control analysis

As described, the speed drop is significant especially in low-speed operation. The most important is the fact that during the cut, the shears are directly connected with material, thus the speed drop of the shears causes slowing down of strip as well. The lower strip speed means the following lower speed reference for the shears, etc. This can be considered as a positive feedback; therefore, it is important to minimise the speed drop.

The second problem is the high load torque with extremely short duration (Table 4). Therefore, the challenge is to design the shears' drive and its control structure to compensate this load impact as fast as possible, thus minimising the speed change during the cut. This task can be divided into two parts: selection of high dynamic drive and design of suitable speed controller.

5. Rotary Shears' Control Structure

Proposed rotary shears' control was designed to be implemented in a commercial inverter. In MPL, shears are usually an individual functional part, employed as a separate drive with its dedicated control system, which monitors the strip speed ahead of the shears. Based on the desired format calculated in the so-called format generator (FG), the shears' control system generates position, velocity and acceleration references for the shears.

The motor control has a cascaded position control structure with feed-forwards (Figure 7), thus the position and speed controllers only compensate inaccuracies in position and speed control. The control structure uses P-type position controller and PI-type speed and torque controllers. It is assumed that the friction is already compensated in the drive.

The position controller together with FG form the so-called technological controller, which can be implemented directly in drive, in a PLC or in another device, and its output is transmitted to the drive via communication bus.

The dynamic torque feed-forward is based on the acceleration from the FG and added to the output of the speed controller.

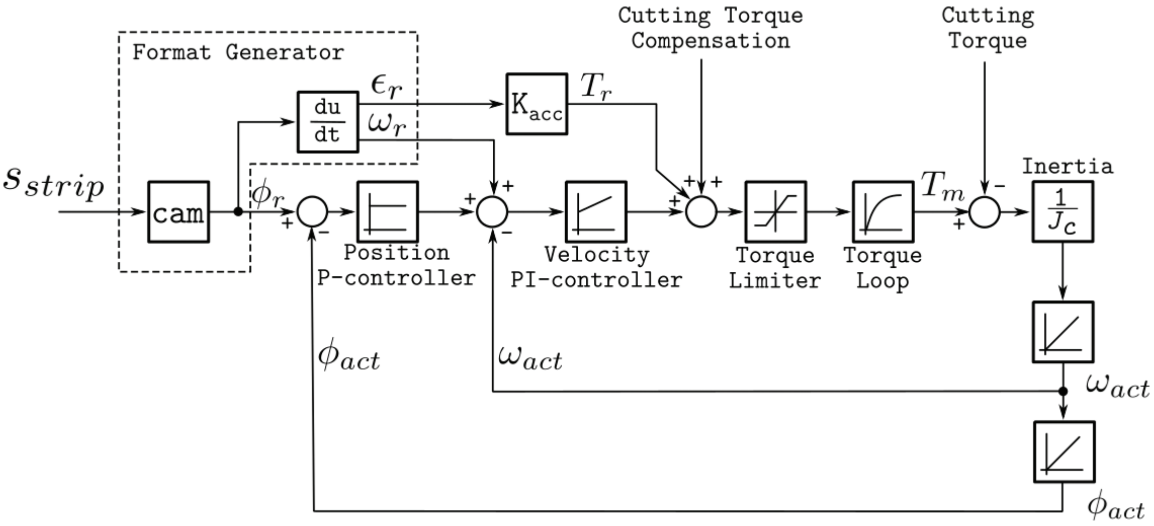


Figure 7. The rotary shears' control structure.

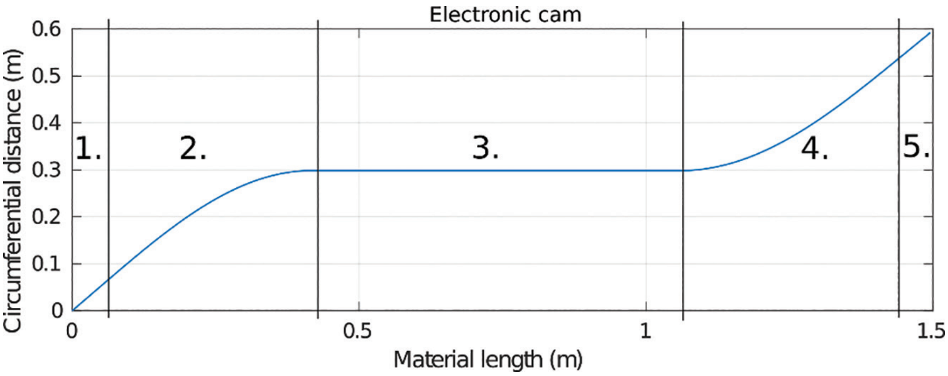


Figure 8. An example of cam.

5.1. Format generator

In the FG, the reference position for the position controller is determined by an electronic cam, which describes the relation of shears' circumferential position to material format length. If the format changes, the cam is recalculated appropriately. There are various cam shapes used in industrial practice, which are selected according to the requirements of mechanics.

An example of cam, which is used in this paper, is shown in Figure 8. The format used in this example is 1.5 m, and the fictitious circumference of the shears is 596.9 mm. The electronic cam is divided into five movement areas which are highlighted in the figure. Starting from RP, the movement areas are:

1. Synchronous speed after cut (shears are in SR).
2. Slowing down (shears are in FR).
3. Steady state (shears are in FR).
4. Speeding up (shears are in FR).
5. Synchronous speed before cut (shears are in SR).

In the synchronous speed after cut, the shears' circumferential speed should be equal or higher than the strip speed to fly away from the material but not to touch or damage the already cut material in front of the shears. In cam, it means that the shears' circumferential distance should rise equally to material distance or a bit steeper, i.e. the slope is 45° or slightly higher. In this example, a 5% steeper slope was used. At the end of area 1, the shears are in FR and the knife is no longer in material path.

Next, the shears can slow down to PP. Here, cam should fluently rise until PP is reached. Here, the PP is at half of the circumference. The shape of this part significantly affects the deceleration, i.e. the speed profile. The steeper cam means the higher deceleration.

In third area, the shears are in steady state in PP, waiting for the material to travel far enough to start the cut. Therefore, the cam is kept in the same value.

When the material starts to reach the requested format, the shears starts to move according the fourth area. Here, the shears should fluently travel to the fifth, synchronous area, in which the shears' circumferential distance should change equally with material distance.

The speed profile, according to the described cam, is illustrated as a ratio of shears' circumferential speed to material speed in Figure 9. In the first area, a ratio slightly over 1 is present, meaning that the shears are faster than material, as was described earlier. The second area represents the deceleration, followed by zero speed in the third area. In the fourth area, the shears accelerate to reach synchronous speed in the fifth area, where the cut is performed.

5.2. Speed controller

The accuracy of the cutting process and smooth operation of the shearing is highly dependent on designed speed controller. To achieve that, the speed controller has two different tasks:

- precise speed reference following before the cut,
- mitigation of the speed drop during the cut.

The precise speed reference following before the cut is crucial for the cutting accuracy. Here, the speed reference is changing relatively slow compared to shears' dynamics. The PI-controller designed by symmetrical optimum method together with feed-forward of the dynamic torque is the most used method for the precise tracking of the reference speed.

During the cut, an immediate reaction of the controller to the load torque is required to maintain shears' speed as close to strip speed as possible. As it can be seen from Table 5 and Figure 10, the response time must be within few tens of milliseconds to effectively compensate the required load torque. In Figure 10, where the single cut at 80 m/min is presented, the material cutting instant is in time from 2.25 s to 2.28 s, i.e. its duration is approximately 30 ms.

The PI speed controller is necessary to accurate tracking of the speed reference before the cut to achieve the highest possible cutting accuracy. However, during the cut, a switch to another controller type is needed and beneficial.

5.3. Load torque compensation

Industrial drives usually have a possibility to add one or more user signals (i.e. feed-forward torque) to reference torque in torque control loop, e.g. to compensate various mechanical losses. In the presented paper, this possibility was used as cutting torque compensation. Its goal is to compensate the load torque (which instantly arises in the

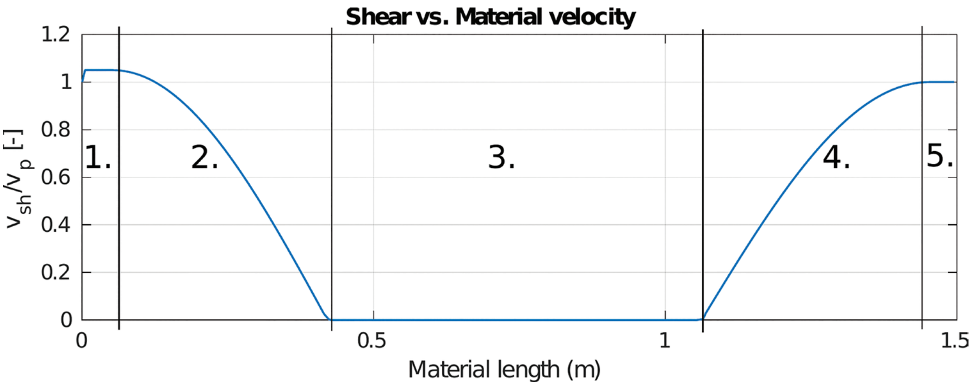


Figure 9. An example of speed profile using cam. A 5% overspeed after cut is shown.

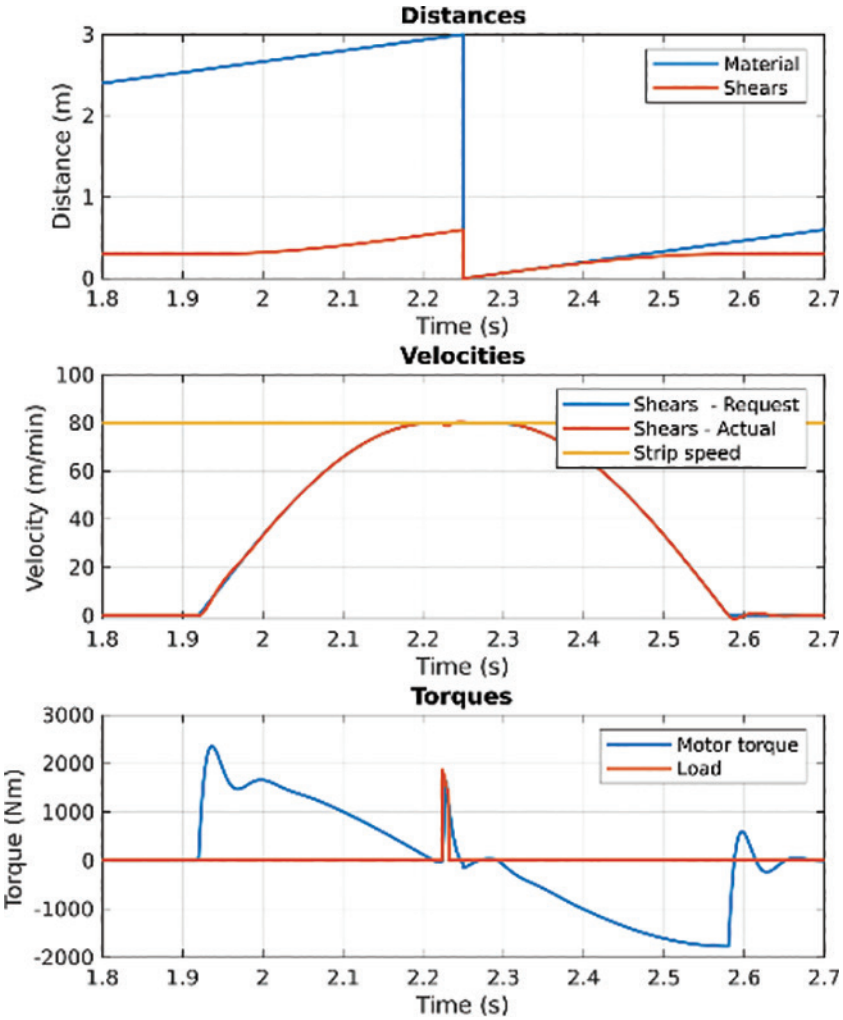


Figure 10. The typical time waveform of the one cut in rotary shears.

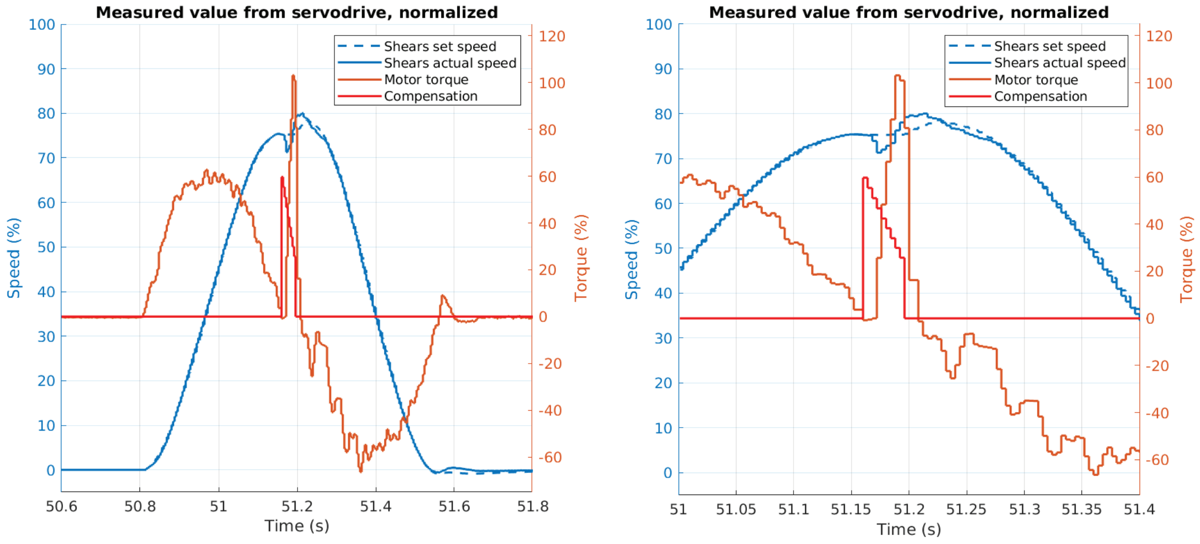
moment the shears cut into material) faster than the speed controller would do and, though, to minimise the speed drop caused by this sudden load.

The shearing torque (i.e. load torque) has a relatively simple shape (Figure 4), which can be approximated by a trapezoidal waveform (Figures 11–16). Its value and duration are usually determined by on-site experiments as it is very difficult to obtain these parameters from calculations due to fluctuating material and shears' properties. However, it can be measured or experimentally found and later predictable considering the material and cutting format.

The load torque compensation is designed in the same shape and added to torque set point (Figure 7). However, the difference with the load torque lies in the value and duration of this compensation. In general, the compensation must be with higher value and shorter duration than identified load torque due to the dynamics of the torque loop. The higher value enables faster response of the torque loop and again, due to torque loop dynamics, it should end sooner as the torque loop response is not immediate. Therefore, it is assumed that the final values are to be determined by trial-and-error method.

The dynamics of drive torque loop is affected mainly by two factors:

- motor parameters affecting the torque loop dynamics, e.g. resistance and leakage inductance of stator and rotor.
- sufficient voltage reserve of the power converter, which enables the compensation of motor time constants and speeding up a torque loop response.



(a) (b)

Figure 11. Experimental results as recorded by Sinamics DC Master with 4 ms sampling time. (a) Whole cut and (b) detail of cutting instance.

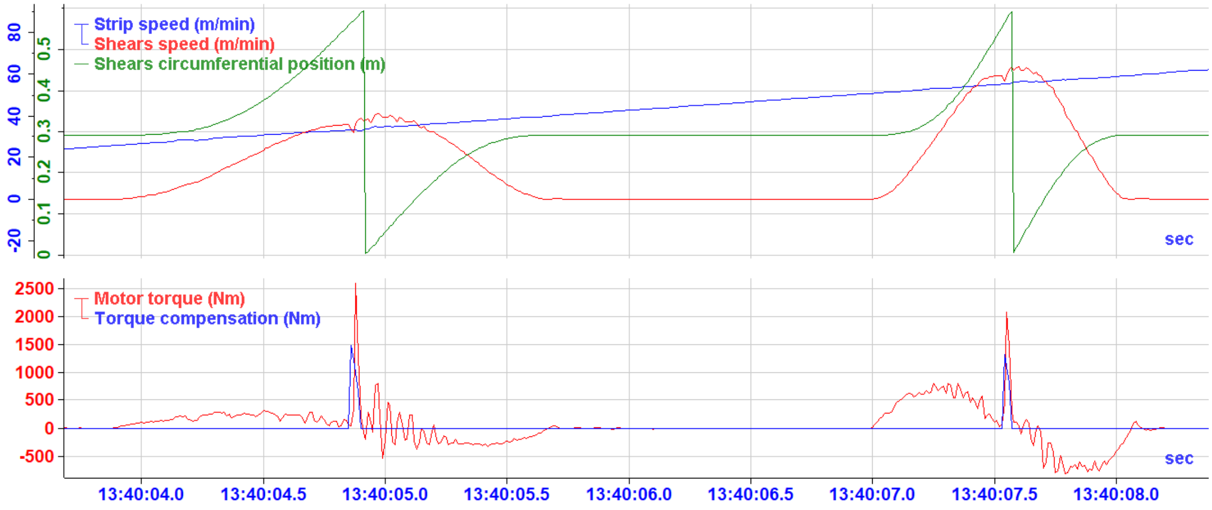


Figure 12. Experimental results during line speed up with 3 mm thick and 1,600 mm wide material.

Using an AC drive with the standard vector control algorithm, a dynamic response of the torque loop is in the range of 5–20 ms, which is comparable to the duration of a load torque. Furthermore, the overall dynamics can be impacted by the communication speed between the technological controller and the drive, which also contributes to a slower reaction of the torque loop. Thus, the load torque cannot be compensated by vector control algorithm and PI speed controller only, hence a non-trivial solution for the compensation of the load torque is required.

6. Problem Definition

The research, presented in the paper, is the reaction to issues that arose during the control system modernisation of existing drum shears in a MPL of steel strips. The basic parameters of the shears are the same, as were used in the analysis in Section 4. These shears were driven by a DC drive, which had slower torque loop dynamics than it would

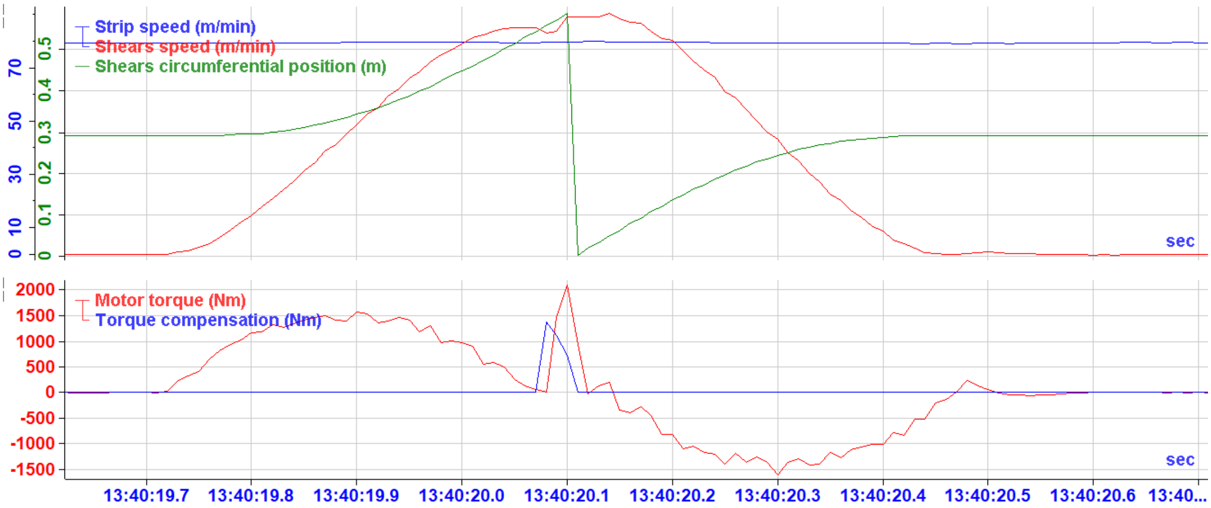


Figure 13. Experimental results at 80 m/min strip speed with 3 mm thick and 1,600 mm wide material.

be in the case of AC drive with vector control. The motor was fed by Sinamics DC master converter. The technology controller was implemented in Siemens Simotion. This set-up had significant limitations that needed to be addressed during the modernisation process: mainly the technology controller cycle time along with communication delay, the response delay of DC converter, caused by its line commutation and the dynamics of torque loop, altogether forming a response time between 8 ms and 12 ms. These limitations also resulted in a 12 ms delay in cutting torque compensation as shown in Figure 11.

The speed controller used was a PI-type controller and an overspeed before and after the cut was employed. The overspeed before cut, with the combination of torque compensation, described in Section 5, ensured the minimisation of the speed drop especially in low-speed operation during the sample cut or line start up, when the shears' kinetic energy was too low to cover the shearing work. However, it is also required in high-speed operation, if thick and firm material was to cut. Overspeed after the cut moves the shears away from material as fast as possible without contact with already cut sheet.

Figure 12 shows the low-speed cutting during line start up, i.e. in 30 and 45 m/min. Using the overspeed before and after the cut together with torque compensation, the speed drop is minimised. In the first cut in 30 m/min, a high torque peak of 2,500 Nm is present, which is required to cut the material in such low speed. In the second cut, the torque peak is lower as higher kinetic energy of the shears is available. In Figure 13, one cut at common operating speed is displayed.

In both figures, a relatively high torque ripple is present. It is caused mainly by losses in the gearbox and mechanics and by the speed fluctuation of the material strip together with relatively high gains of speed controller.

Given the described situations and analyses so far, the main problem is to achieve a high accuracy speed reference tracking during cutting, minimisation of speed drop during the cut and minimisation of speed and torque peaks after the cut, especially during low-speed operation.

Unfortunately, the presented shears are no longer available for experiments as they are fully employed in production process. Therefore, the experimental data presented in this section (Figures 11–13), which have been recorded during the modernisation of the production line in the past, can both describe the problem and partially validate the torque compensation concept.

7. Simulation Analysis of the Torque Compensation and Controller Types

The design and simulation of PI-controller together with simulations containing switching to P- or PD-controller are introduced and investigated in this section. The goal is to demonstrate how the control structure and cutting torque affect the responses of crucial values throughout the cutting process. The observed values are the accuracy of the speed reference tracking and the percentual and absolute speed drop during cutting instant.

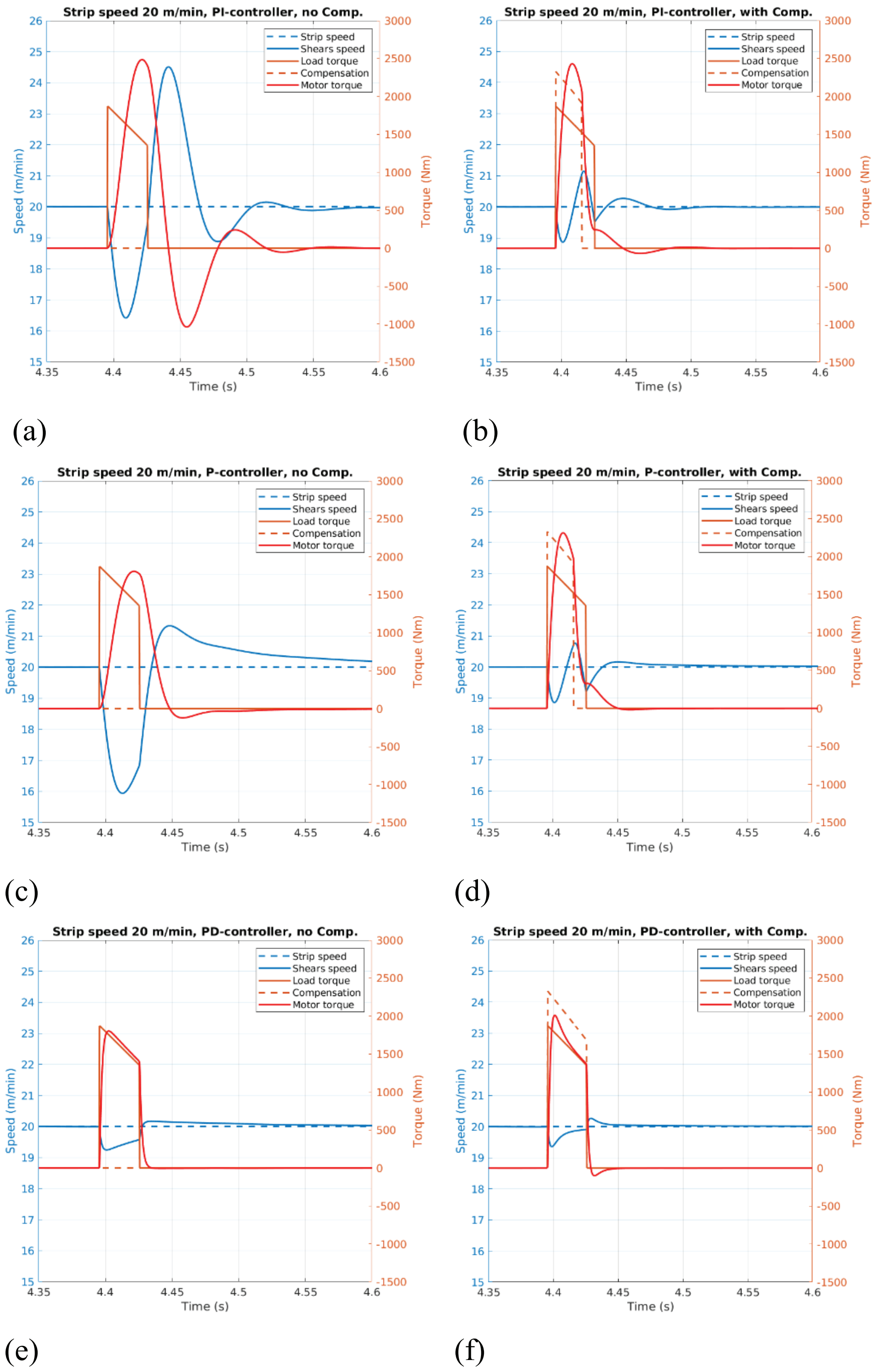
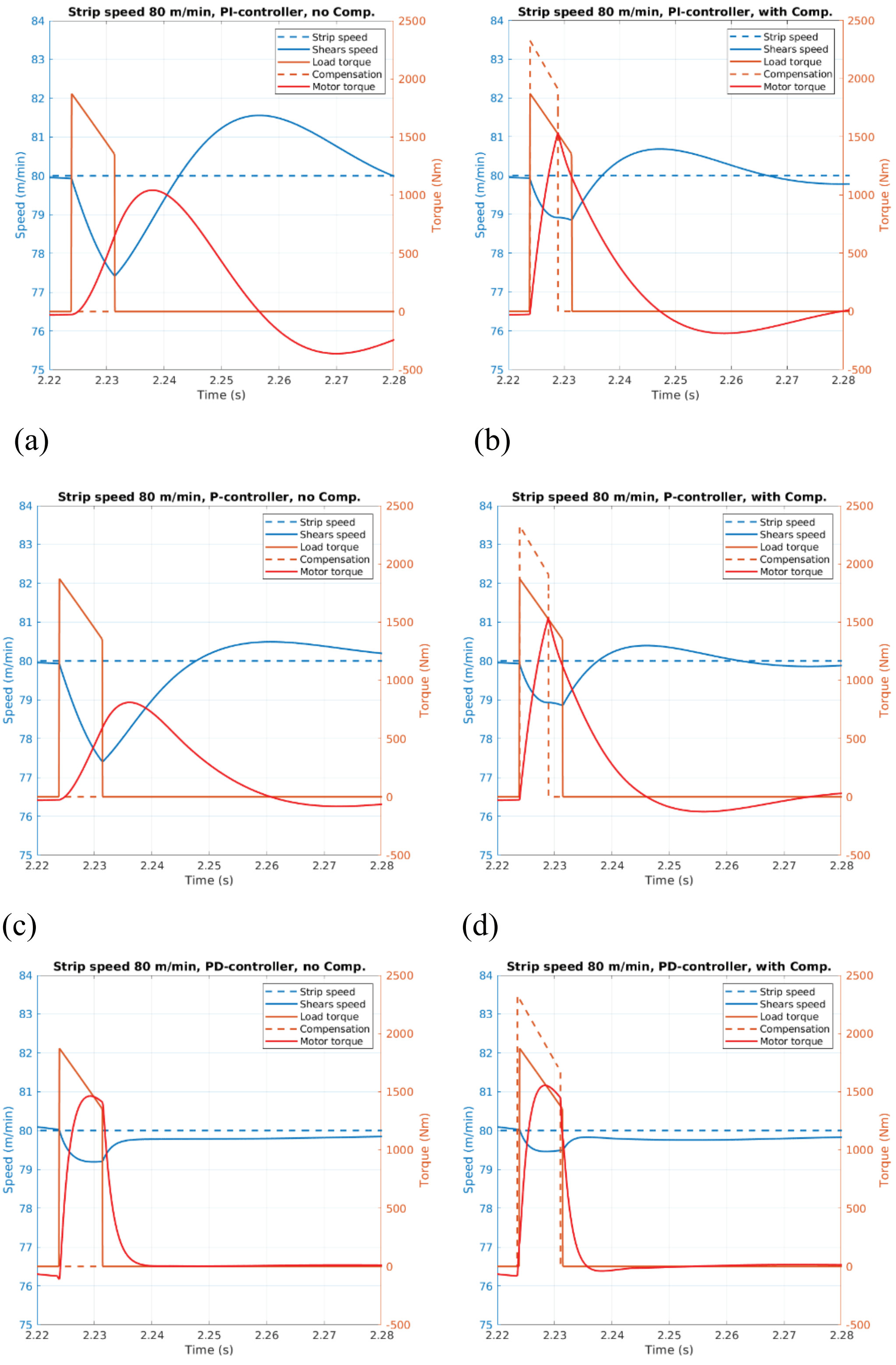


Figure 14. Simulation results of cutting 3 mm thick and 1,600 mm wide strip at 20 m/min. (a) PI-type controller without compensation, (b) PI-type controller with compensation, (c) P-type controller without compensation, (d) P-type controller with compensation, (e) PD-type controller without compensation, (f) PD-type controller with compensation.

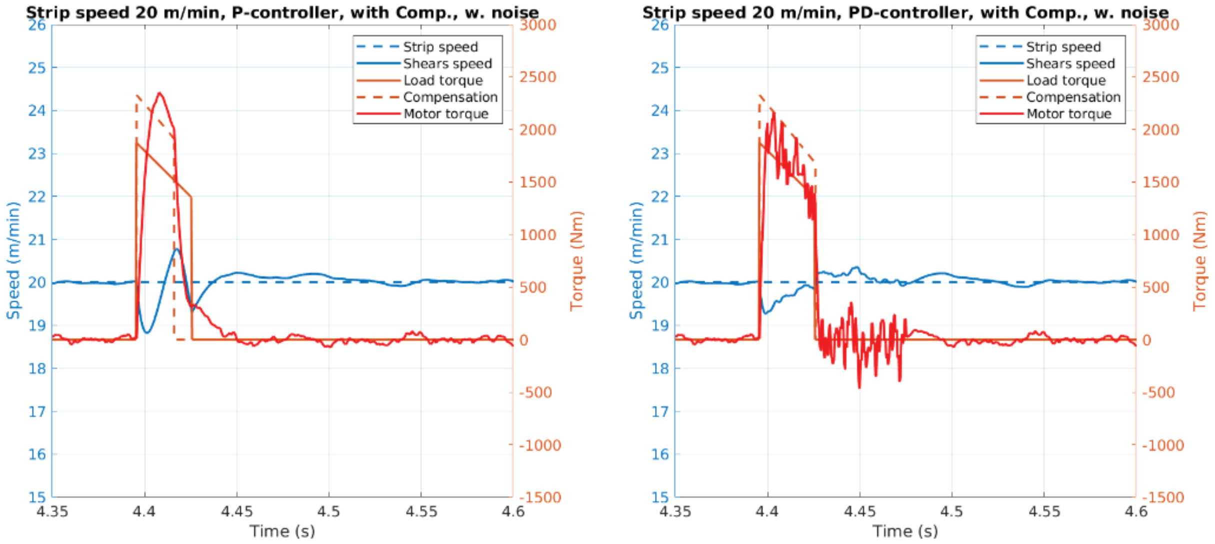


(a) (b)

(c) (d)

(e) (f)

Figure 15. Simulation results of cutting 3 mm thick and 1,600 mm wide strip at 80 m/min. (a) PI-type controller without compensation, (b) PI-type controller with compensation, (c) P-type controller without compensation, (d) P-type controller with compensation, (e) PD-type controller without compensation, (f) PD-type controller with compensation.



(a) (b)

Figure 16. A comparison of simulation results of cutting 3 mm thick and 1,600 mm wide strip at 20 m/min, including white noise in speed evaluation: (a) P-controller and (b) PD-controller.

The simulations were done with the following assumptions:

- the drive has a friction torque compensated,
- the simulation does not consider the possible speed reference changes caused by shears after cut-into instant (positive feedback in speed reference).

Simulation parameters are based on real shears described in Section 4 (Tables 1–3), but instead a DC drive, an induction motor (Table 6) powered by a recuperative frequency converter, is used. The change to an AC drive brings a faster response time of torque loop. Based on authors' experience, the torque loop response time with an AC drive would be around 5 ms. Therefore, in simulations, a torque loop time constant is set to 5 ms as well.

The assumed set-up is as follows:

- the motor is controlled by the Sinamics S120 Single motor module,
- the power DC bus is fed by Sinamics S120 ALM (Active Line Module) with active rectifier,
- the technological controller is implemented in Siemens Simotion D425 controller.

As the motor is not expected to operate in the field weakening zone, the control loops of the torque-producing and flux-producing current components can be modelled by first-order lag as torque loop. The cutting torque compensation is added to the dynamic compensation, which will reduce its delay to minimum (see Figure 7).

The simulations were made for two values of strip speed. At first, the speed of 20 m/min, used for sample cut and final cuts of strip cutting, was simulated. Then, a shears' behaviour during common line working speed of 80 m/min was investigated. The shears' speed controller in FR was calculated by symmetrical optimum method together with feed-forward of the dynamic torque. The gains of investigated P- and PD-controllers in synchronous region, i.e. during the cut, were tuned by trial-and-error method as it would be in practice. The goal was to minimise the speed drop while preserving the reasonable reaction to possible measurement and system noise.

7.1. Simulation results

Figure 14a shows the simulation results of PI-controller without any load torque compensation for 20 m/min strip speed. The load torque is compensated by integral part of PI-controller, which needs some time to accumulate the proper value, causing the speed drop of almost 18%. Moreover, after the cut, the integrator needs some time to decrease its output back to previous value. This causes undesired peaks in shears' speed at the beginning and at the end of the cut. Using the compensation (Figure 14b), the speed drop is significantly lower (approximately 5% of the strip speed) and speed peaks after the cut are also reduced.

Slightly different behaviour can be observed, if the I-component of the speed controller is disabled during cutting, thus temporarily forming a P-controller. The simulation results of this type of controller are shown in Figures 14c,d. This controller, without the compensation of cutting torque, has similar speed drop at the beginning, but significantly lower speed peak after the cut. If the compensation is enabled, the responses are very similar to the PI-controller with slightly faster stabilisation after the cut.

Using the PD speed controller during the cut shows the best results in simulations. The results are shown in Figures14e,f. Even without load torque compensation, the speed drop is minimal; however, incorporating compensation further enhances the responses. Here, the torque compensation has longer duration to minimise the changes that the derivative component needs to respond.

A different situation is in the case of higher material speeds when the kinetic energy of the shears is much higher. The simulations for the strip speed of 80 m/min (Figure 15) shows that in the worst case, the speed drop is only 3.1% (Figure 15a). The lowest speed drop and fastest reaction is with the PD-controller with the load torque compensation (Figure 15f).

7.2. Discussion of simulation results

Various issues and conditions must be considered when implementing presented speed controllers and cutting torque compensation in industrial practice which potentially limit the applicability of proposed controllers. In the first place, industrial servo drives usually do not have a possibility to use a derivative component in speed controllers.

Moreover, there is always a noise present in the measured values, which can cause a high ripple of motor torque or even instability in the worst case. The simulation comparison in Figure 16, using the same white noise in speed evaluation, documents much higher torque ripple using a PD-controller than using a P-controller. Using various filters can mitigate the noise but introduces other problems such as the phase shift or even the loss of information. These two issues practically exclude the possibility to use the PD-controller in industrial environment.

The torque compensation implementation can be challenging as well. Although programming the shape of the compensation is straightforward, its correct placing must consider response time of the current loop and communication delay from technology controller to servo drive. Therefore, torque compensation must be initiated earlier, roughly aligning with the communication cycle time and the torque loop response time.

According to the presented discussion, the best performance is provided by a combination of the PI-controller during shears' acceleration and deceleration phase and the P-controller during the cut with the torque compensation. The variations in required torque compensation, caused by the wear of the shears or other factors, can be compensated by controller. This ensures the minimal speed drop during the cut and minimises undesired speed peaks after the cut.

8. Conclusion

The paper presented a detailed analysis of the cutting process within the rotary shears' operation and compares the shears' behaviour using different speed controller types and cutting torque compensation. As it was shown, the duration of cutting itself is very short. Moreover, within higher line speed, it is even comparable to the dynamics of the drive. Therefore, the speed reference tracking, mainly in high speeds, is really challenging. According to the simulation results and the discussion above, the most suitable solution is to use the PI speed controller in the shears' FR to precisely track the speed reference, thus maintaining the cutting accuracy, and subsequently switch to a P-type speed controller with torque compensation in SR to limit the speed drop and following speed overshoot. After the material is cut, the speed controller is switched back to PI-type. In practice, communication delays and the response time of motor control and its torque loop must also be considered to correctly place the torque compensation.

It should be noted that the similar results are theoretically possible to achieve with highly dynamic PI-controllers (i.e. with very high gains) and no cutting torque compensation or using a PD-controller. However, due to noise, which is always present in the system, the high gains or a derivative component can produce very high torque oscillations.

Although the experimental results were the basis for the presented research, they confirm the suitability of torque compensation to lower the speed drop during cutting, especially in low-speed operation, where the kinetic energy of the shears is low compared to the required shearing work. Unfortunately, new research results cannot be verified in practice, as the shears are no longer available for the experiments.

Acknowledgements

This work was supported by the Scientific Grant Agency and Slovak Cultural and Educational Agency of the Ministry of Education Ministry of Education, Research, Development and Youth of the Slovak Republic under the projects VEGA 1/0363/23 and KEGA 059TUKE-4/2024.

References

Bi, J., Fan, W., Huang, H. and Liu, B. (2020). Reliability Design of an Electronic cam Curve for Flying Shear Machine in Short Materials Cutting. *Journal of Shanghai Jiaotong University (Science)*, 25, pp. 246–252. doi: 10.1007/s12204-019-2106-2

Cinquemani, S. and Giberti, H. (2015). An innovative tool for simulation and control of a flying-cutting machine. In: M. Mains, ed., *Topics in Modal Analysis*, Volume 10. *Conference Proceedings of the Society for Experimental Mechanics Series*. pp. 227-235. Cham: Springer, doi.org/10.1007/978-3-319-15251-6_21.

Ďurovský, F., Šlapák, V., Smoleň, P., Kyslan, K. and Spišák, E. (2023). Rotary shears control in material processing lines. In *2023 International Conference on Electrical Drives and Power Electronics (EDPE)*, The High Tatras, Slovakia, 2023, pp. 1–9. doi: 10.1109/EDPE58625.2023.10274059.

Fetyko, J., Ďurovský, F. and Fedák, V. (2008). Motion control of steel sheet shears with rocking knife mechanism. In *13th International Power Electronics and Motion Control Conference (PEMC)*, Poznan, Poland, 961–966. doi: 10.1109/EPEPEMC.2008.4635392.

Karandaev, A. S., Mugalimov, R. G., Bokov, A. I., Mugalimova, A. R. and Serkov, V. V. (2020). Developing a digital control system for cutting a moving strip to length. In *2020 Russian Workshop on Power Engineering and Automation of Metallurgy Industry: Research & Practice (PEAMI)*, Magnitogorsk, Russia, 107–112. doi: 10.1109/PEAMI49900.2020.9234317.

Madhivanan, N. and Narayanan, K. (2012). FPGA implementation of general purpose real time controller-applied to flying shears in hot rolling mills. In *International Conference on Computing, Electronics and Electrical Technologies (ICCEET)*, Nagercoil, India, 521–525. doi: 10.1109/ICCEET.2012.6203844.

Magura, D., Fedák, V. and Kyslan, K. (2014). Modeling and Analysis of Multi-Motor Drive Properties in a Web Processing Continuous Line. *Procedia Engineering*, 96, pp. 281–288. doi: 10.1016/j.proeng.2014.12.155

Ng, G., Deleanu, S., Prévost, J.-P. and Carpenter, D. (2017). Improving the operation of a flying dividing shear by using Direct Torque Control. In *2017 International Conference on Modern Power Systems (MPS)*, Cluj-Napoca, Romania, pp. 1–8. doi: 10.1109/MPS.2017.7974419.

Peric, N. and Petrovic, I. (1990). Flying Shear Control System. *IEEE Transactions on Industry Applications*, 26(6), pp. 1049–1056. doi: 10.1109/28.62386

Siemens AG. (2001). Sheet-Cutter/Cut to Length for T400 Technology Module. User Manual, software version 1.02, Edition 10.00, Order No.: 6DD1903-0DB0, Siemens AG.

Siemens AG (2004). Simovert MasterDrives – Compendium Vector Control. Edition 04.2004, Siemens AG.

Siemens AG (2007). SIMOREG DC-MASTER 6RA70 Series, Microporcessor-Based Converters from 6 kW to 2500 kW for Variable-Speed DC Drives. Operating Instructions, Edition 13. 11.2007, Siemens AG.

Siemens AG (2011). SIMATIC, Application Module FM 458-1 DP User Manual. Entry ID: A5E01078222-03, Edition 04.2011, Siemens AG.

Siemens AG (2014). SIMOTION Rotary knife V3.0 Manual 1. Application description, Entry ID: 37706606, Siemens AG.

Siemens AG (2015). Cross-cutter application with DCB extension. Sinamics S120 Application example 04/2015, Siemens AG.

Siemens AG (2017a). SINAMICS S120 and SIMOTICS, Motion Control Drives. Catalogue D21.4. Edition 2017. Siemens AG.

Siemens AG (2017b). SIMOTION. Equipment for Production Machines. Motion Control System. Catalog M21, Edition 2017. Siemens AG.

Solomon, M. G. and Gaiceanu, M. (2021). The optimization of the dynamic regime of the asynchronous vectorial AC motor in flying shear. In *7th International Symposium on Electrical and Electronics Engineering (ISEEE)*, Galati, Romania, pp. 1–6. doi: 10.1109/ISEEE53383.2021.9628488.

Spišák, E., Slota, J., Majerníková, J. and Dulebová, Ľ. (2019). Production technologies – forming, cutting, injection molding. *Technical University of Košice*. 1st ed, Košice, ISBN: 978-8-0553-3383-0.

Wang, C., Wang, X. and Zhang B. (2017). Design of the flying shear servo control system. In *2017 Chinese Automation Congress (CAC)*, Jinan, China, 1659–1664. doi: 10.1109/CAC.2017.8243034.

Zang, Y. and Song, X. (2015). The motion control of profile milling flying saw. MATEC Web of Conferences, Vol. 31. In *7th International Conference on Mechanical and Electronics Engineering (ICMEE 2015)*. doi: 10.1051/matecconf/20153103014.