Issues with Belt Guidance and Device Controls in the Automated Conveyor and Drive Belt Perforation Process

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Abstract. The perforation process for multi-layer composite polymer belts presents numerous challenges due to the varied mechanical characteristics and geometrical parameters of the entire range of belts used in the industry. Many problems can be minimized or eliminated with correct development of construction features of the machines for high precision mechanical belt perforation. Regardless of the construction solutions employed in the devices, a major factor influencing the quality of the final product as well as machine reliability is the method of controlling their operation as well as the correct guidance of the belt throughout the entire flow of material in the manufacturing process. The present work provides an analysis of the assemblies ensuring correct belt guidance and presents the causes and effects of incorrect development of these systems. Furthermore, it touches upon the aspects involving the control solutions for such equipment involving the definition of actuators and controllers, the selection of sensors and methods of measuring linear displacement of the belt and perforating head position together with the control algorithms for carrying out different patterns of perforation.

1. Belt guidance in the perforation process
The perforation process for multi-layer composite polymer belts presents numerous challenges due to the varied mechanical characteristics and geometrical parameters of the entire range of belts used in the industry [1, 2]. Many problems can be minimized or eliminated with correct development of construction features of the machines for high precision mechanical belt perforation. Regardless of the construction solutions employed in the devices, a major factor influencing the quality of the final product as well as machine reliability is the method of controlling their operation as well as the correct guidance of the belt throughout the entire flow of material in the manufacturing process.

Belt guidance in the course of the perforation process should be carried out along the entire length of the manufacturing line, from the belt unreeling system and any buffer that may be employed, to prevent continuous operation, through the feeding system which needs to accurately introduce the material to the perforating system, to the module which collects the finished perforated belt. It is critical to maintain the base side alignment at the entire length of the belt, as even a small deviation of approx. 1 mm at the distance of several dozen meters causes to exceed the allowable standard tolerances and destroys the belt. To this end, various gates and stops are to be employed to prevent excessive transverse motion of the belt. At the same time, it should be considered that the belt width may vary by at least a few millimetres along its length; therefore, one needs to facilitate automatic adjustment so that the belt is not blocked or wrapped.

The critical supports are the belt edge grippers (Fig. 1) present in the perforation module MP, directly in front and after the perforating head. Apart from maintaining the base side alignment of the
belt, they are to prevent its motion following a transverse movement of the perforating heads. The base of the gripper uses profile 1 with the defined height, with the bottom plate 2 being mounted on its face surface and the plate acting as a sliding surface for the belt. Bottom plate 2 is mounted to the angle piece 3 with bolts 4, which is subsequently fastened to profile 1 using bolt 5 and t-slot nut 6 placed in the groove R of profile 1. The pneumatic cartridge actuator 7 is fastened to the upper part of the angle piece, secured with two nuts 8 on both sides of the angle piece, which also facilitate its vertical adjustment. At the end of the piston rod 7a of the cartridge actuator 7 a disc gripper 9 is fastened and secured with a lock nut 10. The side surface of the bottom plate 2 allows to fasten the optical gate BO using the mounting plate 11, which allows to adjust the extension of the gate which affects the precision of the perforation pattern, and bolts 13. The profile 1 is fastened to the frame of the perforation module MP using a mounting angle 12 facilitating the adjustment of the gripper in relation to the MP frame. The extension of the actuator is affected by the electro valve. The operating cycle of such gripper entails pressing the belt down as the set longitudinal position is achieved and maintaining this position until the belt moves so that another row of the perforation pattern can be executed.

![Figure 1](image)

**Figure 1.** Belt edge gripper construction in an automatic device for high precision belt perforation: 1 – base, 2 – bottom plate, 3 – angle piece, 6 – t-slot nut, 7 – cartridge actuator, 7a – actuator piston rod, 8 – nut, 9 – pressing disc, 10 – lock nut, 12 – connecting angle, 4, 5, 11, 13 – mounting bolts, BO – optical gate, MP – perforation module

Maintaining insufficient base side alignment results in deviations from the programmed perforation pattern and may cause the belt to twist or block, damaging the product. The optical gate BO is used to detect the presence of the belt, and in the case of misalignment of the base side exceeding the positioning deviation value (e.g. 0.5 mm), the process must be stopped so that the belt isn’t damaged. Additionally, the gate is used to detect the beginning of the belt which improves the belt positioning repeatability. If the process is stopped as a result of malfunction or incorrect belt guidance, it is possible to resume it after the belt is remounted on the machine.

Another major issue is the slip between the driving rollers of the feeding system and the transported belt. This slip is different for different belt types, flat or toothed, and affects feeding accuracy. Therefore, it is necessary to adjust the pressure applied to the belt, and the system should facilitate uniform distribution of the contact stress in order to prevent belt chamfering as a result of velocity vector occurring in the transverse direction in relation to the belt’s motion. Too low pressure on the belt results in no friction coupling with the driving roller; consequently, the motion of the belt is not carried out. Excessive pressure on the belt causes deformation, which can result in a jerking motion (particularly with toothed belts). Based on the studies carried out during pilot production, the optimal pressure values were determined as 1.5 bar for polyurethane toothed belts and 5-6 for coated flat belts,
with external layer of polyurethane, nitrile rubber, plastic fabric or PVC, with actuators with piston diameter equal to 50 mm.

To prevent material waste due to incorrect belt guidance, numerous control systems are utilized to monitor the presence of the belt side and measuring its linear displacement at several points along the length of the manufacturing line. Such a solution enables to compare the values and correct the alignment as necessary so that the programmed pattern of perforation is achieved. Compensating for positioning error entails calculating the difference between the set displacement and the displacement read by the encoder achieving friction coupling with the belt. The difference in value is sent to the BLDC drive controller operating in closed loop in incremental mode. The motion is carried out until the controller receives information about the drive finishing the motion, at which point the difference is determined once again. If the difference does not exceed the threshold value (0.5 mm), the belt side grippers close and the row of holes is being punched. The construction of the device for measuring linear displacement of the belt is shown on Fig. 2.

**Figure 2.** Construction design of the device for measuring linear displacement of the belt when carrying out perforation: 1 – pressure roller, 2 – roller mounting, 3 – carriage, 4 – guide rail, 5 – weight, 6 – measuring roller, 7 – rotation angle sensor, 8 – sensor mounting, 9 – arm, 10 – plate, 11 – axle

The device for measuring belt displacement consists of two rollers: upper roller with bearing and lower rotation sensor roller. The cylinder surfaces of both rollers are in contact with, respectively, the top and bottom surface of the belt. The upper roller with bearing is attached to the device body which is connected to the carriage which moves along the vertical guide to facilitate adjustment of its height, enabling to introduce belts of any thickness between both rollers. Moreover, the upper body to which the upper roller with bearing is connected is fastened to an axle, on which weights can be placed to facilitate variable adjustment of the pressure of the upper roller with bearing onto the top surface of the belt, consequently ensuring the belt is indirectly pressed to the lower rotation sensor roller. This allows eliminating the slipping of the belt surface during linear motion in relation to the rotation sensor roller surface. The displacement of the belt causes both rollers to rotate, whereas the rotation of the bottom roller is registered by the rotation sensor which allows determining the linear displacement of the belt. The bottom roller is set on the axle of the rotation sensor which is connected to an arm
which facilitates angular motion around an axis at one of the ends. Forced angular deflection of the arm is a reaction associated with the arm attempting to assume the starting angular position. This allows eliminating the risk of applying too much pressure on the belt and the rotation sensor roller, which might damage the sensor. The rotating arm discussed above is connected to the base and rotates along an angle. The base is connected to the body of the device in which the belt displacement is to be measured. The measured belt moves on a plate while perfectly adjacent to it, therefore the lower roller of the rotation sensor is extended through a special opening in the plate, slightly above the surface which the belt adheres to.

The design aspects presented above may significantly affect the automated perforation process. However, one needs to point out that they are used in conjunction with control algorithms, which may also cause difficulty in achieving correct pattern of perforation.

2. Controlling the automatic belt perforation machine

Among the subjects related to automatic belt perforation machine controls, one can highlight the following issues: the PI or PID controller settings for used drive systems which enable to achieve the desired process dynamics while maintaining positioning accuracy, perforating head motion sequence programming which minimizes the number of motions and significantly affects the perforation process as well as the operator-machine interface via HMI panel, employment of the required sensors, communication protocols, data acquisition methods and programming the specific perforation patterns.

Fig. 3a demonstrates an example implementation of an automatic belt perforation machine control system. The main component is the programmable controller with HMI operator panel. The drive solutions for perforating heads, the operating drive unit (ZNR) and drive rollers for belt feeding utilize BLDC drive motors together with regulators and controllers communicating via ETHERNET/IP protocol. Belt unreeling and winding is achieved through vector inverter controlled motoreducers, with communications achieved via RS485, additionally, the modules can be operated manually with pedal switches. Controlled pneumatic pressure systems comprise of pneumatic actuators controlled by 3/2 bistable electro valves, whereas Hall effect sensors are installed on actuators in order to detect extreme piston positions. The working units for perforation and cutting with pneumatic actuators are controlled by 5/3 electro valves with two solenoids, with extreme positions being signalled by Hall effect sensors installed on actuator enclosure. Reference positioning of heads and ZNR uses 6 induction sensors acting as limit switches. Additionally, for the purpose of monitoring the state of buffers and module controls for reeling in and unwinding utilizes an additional 8 K1-K8 sensors placed according to the diagram provided on Fig. 3b.

To ensure process continuity without the need to synchronize individual drives, the following states and operations were assigned to individual sensors:

- K1 – empty input buffer → stop perforation and refill buffer,
- K2 – minimum input buffer fill during perforation → restart perforation / begin to fill the buffer,
- K3 – input buffer full → stop operation of unreeling modules,
- K4 – no material in input buffer,
- K5 – output buffer empty → stop operation of the winding buffer,
- K6 – maximum input buffer fill during perforation → restart perforation / begin to unload buffer,
- K7 – output buffer full → stop perforation and empty the buffer,
- K8 – no material in output buffer.

A critical factor influencing the work quality of the perforation machine is the positioning accuracy of the belt and perforating heads. Therefore, it is necessary to determine the controller settings through experimental studies assisted by the drive system dynamics model [3]. In the developed control system, PI (proportional-integral) regulators [4] were used to control both the displacement and speed. After a series of trials, optimal parameters were selected for the designed construction. However, it should be considered that depending on the set displacement, the displacement error and control
overshoot will be different. Based on the results presented on Fig. 4, one can determine that for the displacement value of $x = 10$ mm, the adjustment error stabilizes at approx. $e = 0.75$ mm and the overshoot $p = 2$ mm, for $x = 50$ mm, $e = 1$ mm $p = 3.3$ mm, and for $x = 100$ mm, $e = 1.8$ mm $p = 5$ mm. Consequently, depending on the programmed perforation pattern, it is advantageous to adjust the PI regulator parameters e.g. by employing the characteristics determined on the basis of machine tests. During testing, it was observed that increasing the value of the proportional term $P$ affects the positioning error and overshoot value, whereas the setting of the integral terms $I$ affects the stabilization time of the positioning error. Extreme regulator setting values are to be avoided as too high values introduce a resonance in the system which may damage the device.

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Figure 3. Example implementation of the control system for automatic belt perforation: a) conceptual diagram, b) placement of sensors in buffering modules: K1-K14 – inductive proximity sensors, LS1-LS5 – magnetic piston positioning sensors, EC1-EC5 – electrovalves with solenoids, PA1-PA10 – pneumatic actuators, MR1-2 – motor reducers, SE1-4 – BLDC electric motors, PLC – programmable logic controller, 4×N5 - BLDC electric motors regulators, PN1-2 – pedal switches
To facilitate carrying out any perforation pattern programmed by the user, it is necessary to develop complex algorithms for calculating the coordinates for subsequent holes, while keeping in mind the requirement to minimize the motions of the head. The present work discusses machine controls used to achieve one of the two basic patterns of perforation: rectangular (A) or displaced (B), presented on Fig. 5 together with programmable parameters.

The presented control method (Fig. 6 and 7) is based on calculating hole coordinates and operating in an absolute system of reference in which the zero point is determined at every startup of the machine using limit sensors, through free motion of the heads until the sensor is triggered. One needs to consider that the travel speed is highly important from the standpoint of transverse positioning. For each row, the controller calculates the coordinates and sends them in a sequence to the regulator unit of the respective drive motor, until the $i$ incremental counter reaches the value equal to the number of columns in the perforation pattern. In the case of pattern A, the coordinates do not change, whereas for pattern B, every second row has different coordinates. Displaced patterns are also used, in which every other row has one fewer hole. To achieve such a pattern, the controller checks the reminder of the division of the current row number by 2, and subsequently, depending on the result, instructions are carried out from branches A or B, where the displacement value $x_p$ is taken into account, or condition to end the conditional instruction from „equal to or lower than” to „lower than”. Additionally, the controller constantly monitors the buffering system, operating the systems for unwinding and reeling in at branches N and O. In order to make the hole, the electrovalve is engaged to switch the solenoids after the signal from actuator end sensor is received.
Control algorithms for more complex patterns, e.g. double row or interrupted patterns, can be developed in a similar way. If the perforation pattern calls for punching holes with different diameters, a repeatable pattern of positioning is necessary, so all the holes with a given diameter can be made in a single pass. All the above mentioned aspects necessitate a long startup time for the machine, despite the deceptive simplicity of the process, as multiple tests are required to verify the degree of achieved accuracy.

Figure 6. Control algorithm for belt perforation device according to patterns A and B – part 1

Figure 7. Control algorithm for belt perforation device according to patterns A and B – part 2
Conclusions
The issues described in the present work confirm that within a mechatronic system, the discussed design being such, both the construction design and device controls are important for the final result of the machine operation. It needs to be pointed out that both issues are difficult to separate as they will affect one another to a great extent. However, by following the recommendations provided in this work, it is possible to significantly improve the design process for the control systems of these machines and the presented issues can be applied to other machining processes involving belts and strips.

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