Development of inline closed-loop vibration control in progressive die stamping using finite element simulation

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Abstract. Modern progressive dies are increasingly equipped with integrated sensors and actuators, thus enabling an improvement of the manufacturing process and an inline monitoring of the component quality. The design of the tooling is determined at an early stage and is largely based on the desired product and the specific production stages such as blanking, forming and punching. Nevertheless, malfunctions such as strip vibrations cannot always be foreseen and may occur during operation time, which may lead to reduced component quality and in the worst case to component collision or a damage of the tooling. Therefore, complex reworking or a reduction of the stroke rate and thus lower output quantity are often necessary for a reliable and stable process. Strip vibrations are often caused by the highly dynamic transportation of the strip in the tool and can have various causes. Among others, passive tooling components such as spring-loaded, hard stop limited strip lifter can be the cause of such vibrations. Strip lifter are always necessary when three-dimensional components are produced and have to be lifted out of the die for the feeding phase. The feeding phase takes place between two strokes of the stamping process. This work is aiming for a control strategy to suppress strip vibrations in various progressive die stamping processes based on closed-loop controlled active strip lifter. These strip lifter combine the spring-loaded passive standard strip lifter with an additional PID-controlled actuator. Taking the dynamics of the flexible strip during operation into account, a Finite Element Analysis (FEA) model of a progressive die tooling system is created. For the design of the control algorithm, the FEA model is connected to an environment for model-based design in a co-simulation. This approach allows modelling the influence of arbitrary control parameter settings on the movement curve of the strip, aiming for an increased stroke rate.

1. Progressive Die Stamping

Progressive die tools are used in the field of the automotive, the electronics and the household appliance industry to produce predominantly flat parts from sheet metal. A progressive die tool consists by definition of multiple individual stages, through which the strip of sheet material runs progressively. Each of these stages performs one or multiple manufacturing operations on the part. Transport of the strip is done by a carrier strip, which holds the part with stretch web connectors. The sheet metal is usually presented as coiled strips, unwound by decoiler systems and fed into the press by roll feeding machines. With each stroke, one or multiple parts are produced at the end of the tooling. In case of deep drawing operations or three-dimensional regions on the part, strip lifters are often used to lift the strip up from the die. The aim of this lifting is to avoid collisions between tooling components and the strip in order to maintain a safe part transport. Due to high acquisition costs of the tools, progressive die stamping is mainly used for high-volume production and is therefore designed to operate at a high speed. As a result, vibrations of the strip need to be reduced to enable higher stroke rates while maintaining a precise positioning of the strip in the desired position. The design of the strip-layout and the tool are the...
subject of current research aiming to maintain a safe operation of the tool at an early stage of the design process. [1], [2]

As shown in figure 1, a progressive die tool consists of a base die plate, a top punch plate and several single manufacturing stages which can be guided to each other by column guides. In each module, there usually is a punch plate, a die plate and a blankholder plate which is connected to the punch plate by coil or gas springs. The active parts for the forming operations of each step are mounted on the punch and the die plate.

![Figure 1](image1.png)

**Figure 1** Components of a progressive die tool with three modules and spring loaded strip lifter.

In operation, the tool is mounted inside the press machine and a producing stroke starts at the top dead center (TDC) with the press ram going down (phase I). With the blankholder going down, the strip is pushed towards the die. In this phase, the strip is often positioned by pilot pins. During the downward movement of the strip, the coil loaded spring lifter guiding the strip, is compressed. After the strip is fully clamped against the die in its designated position, the actual operation process begins with the punches being pushed towards the strip. Deep drawing, cutting, embossing and other operations must be finished until the blankholder releases the strip from being clamped. The lower position of the press ram is called bottom dead center (BDC, phase II) and represents a half stroke of the press machine. After the forming process the tool opens and the compressed spring of the strip lifter follows the movement of the blankholder towards its upper position. The designated position of the strip for transport is maintained via stop plates, which force the strip lifter to immediately stop their movement (phase III). This abrupt stop induces an impact into the strip lifter and causes it to transmit vibrations on the strip. Another cause for vibrations on the strip is the inertia of the strip itself. Shortly before reaching the stop position, the strip has a velocity in the upper direction, which leads to an overshoot of the strip. During the vibrating period, the strip alternately strikes between the boundaries of the guiding gap. This introduces multiple impacts on the strip. The guiding of the strip and the operation phases of the progressive die are shown in figure 2. There are several patents for the passive design of strip lifter, whereas the active control of the movement curves is still poorly researched. [3], [4], [5]

![Figure 2](image2.png)

**Figure 2** Phases of Progressive die operation and strip guiding gap on the strip lifter bolt.
2. Co-simulation

2.1. Overview of co-simulation structure

One aim of this work is to implement a closed-loop control using a finite element tool, a numerical computing environment and a graphical block diagramming tool.[6], [7] The possibility of coupling a finite element simulation in Abaqus 2018 with a controller model implemented in Simulink has already been shown in [8] using subroutines. In the following, the approach of using the restart functionality in Abaqus and connecting it to Matlab R2018b/Simulink 9.2 is described. The co-simulation is performed using a Matlab script, which is used to coordinate the different building blocks and is executed as a closed loop controller. Figure 3 represents the structure of the co-simulation as a block diagram.

![Figure 3 Block diagram of the structure of the developed co-simulation approach](image)

Before the start of the simulation a simplified progressive die tooling was designed using Catia V5. The CAD design is then forwarded to the Abaqus/CAE environment as a step file (ProgressiveDie.stp). In the Abaqus model an initial input file (restart_0.inp) is generated. Based on this input file the simulation is initialized and the boundary conditions for modelling the behavior of the tool are set. This first input file can then be accessed from the main Matlab file (CoSim.m) using the command line. As an outcome of the first simulation, in Abaqus the results are written into the restart_n.odb file. The .odb-file is opened with a python script (output.py) in the Abaqus python API environment, which extracts the results information needed to control the lifted strip in the model. Specifically the load curves of the strip lifter, the displacement curves on several characteristic points of the strip and the displacement curves of the strip lifter are exported into an output_n.txt file. These movement curves serve as input signal for a Simulink model (Cosim.sli), which compares the current displacement of the strip with a reference value and determines a load with the help of a PID controller. The new load forces of the strip lifter are then forwarded to Matlab, where a new input file (restart_n+1.inp) for the next loop iterations is created. The load and displacement curves for this iteration are also saved. The new input file is then again processed in Abaqus and the results are saved as restart_n.odb, which indicates the next iteration of the co-simulation loop.

2.2. FEA Abaqus Model

The Abaqus model of the progressive die tooling used to create the input files for the co-simulation is shown in figure 4. The strip is pushed down and lifted to a height of 20 mm within each stroke. On the left side of the tool is a strip guidance, which defines the upper position of the incoming strip and two feeding rolls. They represent the feeding machine transferring the strip through the tool. The progressive die tool contains three modules consisting of a die, a punch plate and a blankholder respectively. module A represents a blanking station, module B a forming station and module C a cutting station, which cuts off the produced part at the end of the manufacturing process. The tooling is modelled without the active components for the actual forming and cutting processes in the modules to focus on the lifting operation during the strip movement. Each station has one strip lifter on each side of the strip with a guidance gap of 0.7 mm.
Figure 4 Assembly of the progressive die tool and layout of the investigated strips.

For the passive model configuration, the strip lifters are implemented spring-loaded with a linear spring (figure 2) with a spring rate of 5 N/mm. The force acting on the strip lifter is described in equation (1) as a function of the vertical strip lifter position $z$ and the vertical strip lifter position $z_0$ at which the spring is in its designated upper position:

$$F_{SL,passive} = c \ast (z - z_0)$$  \hspace{1cm} (1)

For the active strip lifter, a force $F_{control}$ acts via single point force in addition to the spring. For an actuator modelled with ideal dynamics, the total force $F_{SL,active}$ is applied to the strip lifter:

$$F_{SL,active} = c \ast (z - z_0) + F_{control}$$  \hspace{1cm} (2)

The tool components are modelled as rigid shell bodies to handle simulation times and maintain a good contact behavior with the strip material. Four types of strips are modelled in order to consider different cases of progressive die stamping. Each of the strips has a thickness of 0.5 mm and is modelled using shell elements (S4R) with an AA5182 material. The meshed strips are shown in figure 4.

The full strip, v1 is used to set up the model and to tune the PID controller implemented in the Simulink model. The strip layout single tracked, double carried, v2 represents a configuration for a single, bigger part, which is connected to two outer carrier strips and is considerably more likely to have vibrations on the part while lifting. Whereas, the strip layout double tracked, triple carried, v3 is supposed to have more vibrations relating the whole area of the part and stretch web connector. This configuration represents a tooling for producing two parts per stroke. A configuration which is sometimes chosen for small products is represented in the strip layout single tracked, single carried, v4, where the carrier is applied to just one side of the product, which leads to a high amount of vibrations on the unsupported side of the strip. Due to its geometry, this strip is only in contact with one of the two strip lifters.

2.3. Simulink Control Model

The control algorithm for reducing the vibrations in the strip was modelled in Simulink. As input signal, the Simulink model receives the vertical position at three points (part1, part4, part6 - figure 4) on the strip from the Matlab master script. This signal represents the feedback signal of the control loop. In the target curve function block, an arbitrary target trajectory can be specified as the reference variable for the vertical position of the strip. The control deviation is the difference between the reference variable and the read-in values of the controlled variable. Within the Simulink model, the force to be applied by the actuators at the three independent pairs of strip lifters is calculated from the control deviation. This actuating signal is written into the Matlab workspace and is thus available to the Matlab master script.

To calculate the actuating signal, a separate PID controller was implemented for each of the three spring lifter pairs. A PID controller is used as a universal type of control loop mechanism, which is a parallel combination of a proportional term, an integral term and a derivative term. In [9] a PI controller
was used for vibration suppression of a beam structure and in [10] a PID controller was used for damping the vibrations of a smart beam. In [11] a PID controller is applied to the problem of vibration control of a cantilever beam. An ideal PID controller has the transfer function, including the three gain factors $k_p$, $k_i$ and $k_d$, shown in equation (3):

$$K_{PID}(s) = k_p + k_i \frac{1}{s} + k_d s$$

(3)

The behavior of the PID controller is characterized by the value of these three gain factors:

$k_p$: The proportional gain factor leads to a rapid reduction of the control deviation, but cannot usually correct it completely. An increase of this factor can result in an increased overshoot of the system when a step excitation is applied.

$k_i$: The integral gain factor leads to a slow response of the controller. In contrast to the other two control components, however, it enables a complete correction of the system deviation for a step excitation.

$k_d$: The derivative gain factor cannot be used as a stand-alone controller, since it does not carry out any control intervention for any constant control deviation. A further disadvantage is that an existing measuring noise is amplified. It is advantageous that the controller provides a high control signal even in the case of a small control deviation but a high increase in control deviation.

For the real implementation of the derivative term shown in equation (4), an additional filter coefficient $N$ is integrated. This formulation leads to a lower sensitivity to a noisy input signal. The output $K_{PID}$ of the controller is forwarded to Abaqus as a single point force signal for each strip lifter:

$$F_{control} = K_{PID}(s) = k_p + k_i \frac{1}{s} + k_d s \frac{N}{1 + N \frac{1}{s}}$$

(4)

Furthermore, a saturation limit of 150 N was chosen for the actuation signal. This is necessary to model the physical input limits of the actuator. To avoid integration-wind-up when the saturation limit is reached, the back-calculation anti-windup mechanism implemented in the Simulink PID controller block was chosen. This algorithm leads to a discharge of the output of the integral gain. The investigated section, the derived step excitation and the actual movement curve of the part are shown in the figure 5.

![Figure 5 Investigated section of strip movement, step excitation and the actual movement of the strip](image)

### 3. Results

In the following section the simulation results of the closed-loop controlled system containing active strip lifter are compared to the reference system configuration relying on passive spring strip lifter limited by a hard stop. The co-simulation model enables the automated execution of a parameter study, in which the effects of different control parameter configurations on the system behavior of the FEA model can be compared. The gain parameters of the PID controller $k_p$, $k_i$ and $k_d$ were varied within a reasonable value range for the full-strip configuration. As will be shown in the following section, the parameter configuration in table 1 allowed a reduction of the amplitude of the occurring oscillations compared to the uncontrolled model. The visualization of the simulation results is therefore carried out for all investigated strip layouts using this parameter set.

| Stroke rate | Lifting distance | Step size | $k_p$ | $k_i$ | $k_d$ | Lifter spring rate | Strip thickness |
|-------------|-----------------|-----------|-------|-------|-------|-------------------|----------------|
| 120 1/min   | 20 mm           | 0.01 s    | 1     | 2     | 0.01  | 5 N/mm            | 0.5 mm         |
In the passive system, vibration of the strip is excited by reaching the hard stop at the end of the lifting phase. At a high stroke rate these oscillations can cause the strip to be released from the guide gap in the subsequent feeding phase. Furthermore, high vibration amplitudes can lead to a collision of the part with tool components. The aim of implementing closed-loop controlled active strip lifter is to increase the possible stroke rate compared to the uncontrolled configuration. This is to be achieved by lowering the maximum oscillation amplitude during the feeding phase. Therefore, the lifting and the feeding phase is examined for each of the four tested strip layouts. In figures 6 to 9, the vertical displacement of the six measurement points on the strip are shown. The lifting phase starts at t=0.32 s. The shown time steps display the moment where one of the reference points first reaches the desired 0 mm displacement.

3.1 Results full strip, v1

For the full-strip layout seen in figure 6, the uncontrolled reference system exhibits continuous strip oscillations around the reference value during the feeding phase. In the controlled system the maximum amplitude of the oscillations can be reduced by 44.01% compared to the reference system. A comparatively high undershoot occurs immediately after the set point position is reached for the first time. Subsequently, the vibration amplitudes continue to drop. A comparison of the two configurations shows that in particular the high-frequency portion of the oscillations is compensated. The duration of the lifting phase is approximately the same for both configurations.

3.2 Results single tracked, double carries, v2

For the single tracked, double carries layout shown in figure 7, the uncontrolled reference system exhibits considerable strip oscillations around the reference value during the feeding phase. In the controlled system the maximum amplitude of the oscillations can be reduced by 44.01% compared to the reference system. A comparatively high undershoot occurs immediately after the set point position is reached for the first time. Subsequently, the vibration amplitudes continue to drop. A comparison of the two configurations shows that in particular the high-frequency portion of the oscillations is compensated. The duration of the lifting phase is approximately the same for both configurations. 
For the configuration *single tracked, double carried*, v2 shown in figure 7, the vibrations occurring in the feeding phase are similarly reduced. The vibrational amplitude is decreased by 10.73%. The duration until the feeding height is reached for the first time is slightly higher in the controlled system.

### 3.3 Results double tracked, triple carried, v3

**Figure 8** Comparison of reference and controlled analysis of the strip movement for strip-layout v3.

Also for the *double tracked, triple carried, v3* configuration represented in figure 8, a reduction of the maximum vibration amplitude during the feeding phase is reached by introducing the controlled strip lifter. This is a decrease of 51.32%. However, in this case the controller introduces strip oscillations during the lifting phase. As these are less pronounced than the oscillations in the feeding phase, they do not represent a limiting factor for the maximum possible stroke rate.

### 3.4 Results single tracked, single carried, v4

**Figure 9** Comparison of reference and controlled analysis of the strip movement for strip-layout v4.

For the layout *single tracked, single carried, v4* shown in figure 9, the passive system has a comparatively high duration of the lifting phase compared to the strip geometries discussed above. By introducing the active lifter, a reduction of the rise time is achieved. Furthermore, the controller does not introduce any significant additional vibrations during the lifting phase. During the feeding phase, oscillations continue to occur in the controlled system, but these have a reduced maximum amplitude of 53.01% compared to the passive system.
Conclusion

Closed-loop control for reducing the amplitude of strip vibrations in a progressive die tool was realised in a co-simulation model composed of a FEA model and a Simulink control model. By using the Abaqus simulation restart functionality, the FEA simulation could be divided into single steps, whose length corresponds exactly to one time step of the controller. This approach enables to connect the FEA model with arbitrary control algorithms and to analyse the influence of various control parameter settings on the system response during the runtime of the FEA model.

Three pairs of active strip lifters combining the passive spring with a PID controlled actuator were integrated in the FEA model. Several factors, such as the alternating tapping of the strip in the guiding gap lead to a highly non-linear behavior of the system response. On four variants of progressive die strips, testing of the vibration reduction was done for various gain parameter settings of the PID controller. By this control approach, an improvement of the vibrational behavior of the investigated strip-layouts was achieved. However, depending on the strip geometry, a varying amount of residual vibrations remains. Therefore, in future work, a strip geometry specific tuning can be applied. For example, a controller design in the co-simulation model with a reinforced learning approach can be useful to deal with the complex dependencies of the system.

The results can be used in industrial applications by replacing passive, spring-loaded strip lifters with active force or displacement controlled actuators, like linear ball screw actuators or voice coil motors.

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