Study on pre-acceleration characteristics of servo motor applied on stamping die cushion

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Abstract. In this study, a servo motor controller having only the mutually exclusive switching function between velocity and force control is used to set up a servo mechanical die cushion to explore the technology of force control that can enable the cushion to obtain the pre-acceleration function. Under different torque settings of the servo motor, the final velocity and the travel stroke of the die cushion for a certain time duration have been investigated for each response surface. A design scheme to determine the setting parameters for the pre-acceleration of the die cushion, such as the torque and the time duration, in which its both response surfaces of the velocity and the stroke are used, is thus proposed and verified by examples. The results show that the design scheme is indeed feasible and would be available for corresponding technicians’ reference.

1. Introduction

Sheet metal stamped products are often used in daily life. Because of their rigidity due to work hardening of metals and high geometric complexity, they are easily found in household kitchen utensils, tableware, electronic products, automobile body panels, aircraft skin, etc. [1]. Furthermore, they have economic benefits in manufacturing, such as saving materials, fast processing, and mass production [2]. To stamp a sheet metal blank into a part, the outer area of the blank is clamped first, followed by the shape of the punch being geometrically imprinted on the sheet by a subsequent shallow punch travel to the die cavity. The side wall of the part is then formed, during which the outer area of the blank flows into the die cavity by controlling the blankholder force while the punch is travelling to its bottom dead center. After the previous stamping process, the punch retracts its top dead center and the part is picked out. If the blankholder force is too small, wrinkling will appear on the outer area of the blank, while tearing will appear around the punch radius if the blankholder force is too large [3-4]. It is still a challenge for press-shops to stamp a good part by providing an adequate blankholder force during the stamping process. The most common approach used in press-shops is that a die cushion is equipped underneath the press bed and provides the blankholder force to the die set via pins through the press bed and the base plate of the die set [5]. However, due to the contact of the die mounted on the moving ram of the press with the blankholder supported by the stationary die cushion, an impact and thus noise is generated [6]. Therefore, the pre-acceleration function of the die cushion, which is driven by a servo hydraulic proportional valve, can be accordingly implemented to have the blankholder fall rapidly before the die approaches it. With the pre-acceleration, the blankholder can be accelerated so that its velocity is close to the die speed at the end of pre-acceleration stroke, in order to reduce the impact of the die on the blankholder [7]. Though the pre-acceleration has been in place by equipping hydraulic servo valve, this practice still has some disadvantages, such as complex manifold and pipeline, poor hydraulic response, excessive energy consumption, and inaccurate top dead center position [8]. Nowadays, a new cushion
system has been proposed [9]. The system uses a servo motor to directly connect a screw and nut to drive the cushion pad, so that the pre-acceleration function can be achieved by simultaneously applying motion and force control to the servo motor [10]. However, this complex control mode scheme is not applicable to the servo motors available in the market, whose motion and force control can only work mutually exclusively to each other. Thus, this research attempts to explore the feasibility of using the above-mentioned servo motor, whose controller is the only available type in the market, to make a servo mechanical die cushion having the pre-acceleration function.

2. Functions of die cushions working for stamping process

During the stamping process, the movement of the die cushion is repeated according to the movement of the press ram. The relationship between the movements of the die cushion and the press ram is schematically shown in figure 1. The horizontal axis is the rotation angle of the crank driving the press ram, where 0° is usually the crank angle of the upper dead center of the press ram, while the vertical axis is the stroke of the press ram as well as the stroke of the die cushion. The solid line in figure 1 shows the movement of the die cushion in relation to the movement of the press ram, shown as the dashed line. There are usually six operation stages during working with the die cushion: placement, pre-acceleration, drawing, holding, pickup, and lifting. The placement stage comes from the lifting stage of the die cushion in the previous operation cycle. After the die cushion rises to its top dead center, it stays there for the operator or robot to place the blank. The pre-acceleration stage is to accelerate the die cushion downwards from the top dead center, so that it has a velocity close to that of the press ram at the end of the stage. The drawing stage is when the die mounted to the press ram contacts the blankholder supported by cushion pins along with the die cushion, and then the die cushion follows the press ram to continue downward while providing blankholder force for the drawing process by resisting the press ram downward motion. In the holding stage, the die cushion will stay at its bottom dead center for a while after the drawing process is completed. The workpiece is thus retained on the punch, not with the die mounted on the press ram ascend, in order to prevent the workpiece from being clamped in the die cavity, which is caused by springback of the workpiece and makes the part difficult to position for pickup after ejecting from the die cavity by the knockout. The die cushion rises a little bit later in the pickup stage to separate the workpiece from the punch and to hold it on the blankholder at a certain height for facilitating the operator or robotic to pick up the workpiece. The lifting stage is when the die cushion rises back to the preparation point and is ready to continue the next cycle.

![Figure 1. Schematic working cycle diagram of die cushion.](image)

Because in the drawing stage the pins and the blankholder contact the die to form the processing force line, a load or torque control mode must be performed in the controller of the servo motor in the die cushion so that the die cushion can follow the motion of the press ram driven in a mode of velocity
control and simultaneously provide the blankholder force. Because there is no load needed to provide in the other stages, the mode of velocity control can be applied for the motion of the die cushion. However, the transition from the pre-acceleration stage to the drawing stage is very important. At the end of the pre-acceleration stage, if the speed of the press ram is faster than that of the die cushion, an impact still occurs when the die contacts the blankholder. The impact will affect the load control for the subsequent drawing process. Therefore, the die cushion’s acceleration must be carefully controlled to have a speed close to that of the press ram from the stationary state at its top dead center. However, this study intends to apply a servo motor for the die cushion, which has a controller whose motion and load control modes are mutually exclusive and can be switched only under the condition that the servo motor must completely stop. Since at the end of the pre-acceleration, the die cushion has to be in a moving state, the velocity control mode cannot be applied for the pre-acceleration stage; otherwise the speed accelerated in this mode must be reset to zero before the load control mode can be switched to perform the drawing stage, which means the pre-acceleration is in vain and the die still hits the stationary blankholder at a high speed. Thus, the pre-acceleration must be operated in the load control mode. Fortunately, the previous stage prior to the pre-acceleration is the placement stage, in which the die cushion stands still at its top dead center, providing the possibility to switch the control mode. Consequently, this study attempted to pre-accelerate the die cushion in the load control mode. Depending on the height of the stamped workpieces, the stroke of the die cushion for drawing will be different. As shown in figure 1, there are three variations of curves for three different heights. However, the die cushion has the same top dead centers but different bottom dead centers for the three workpieces. For the taller workpieces with a longer drawing stroke such as variation 1, when the die contacts to the blankholder, the speed of the press ram or the slope of the stroke curves will be higher, because its crankshaft angle is smaller. Thus, it needs a larger torque to accelerate or longer time duration to travel the stroke for the pre-acceleration stage. Furthermore, due to the geometric complexity of the stamping part, the drawing process must slow down the drawing speed to form rounded corners and details, which can be done by reducing the strokes per minute (SPM) of the press ram. At the same time, to increase the production rate, the forming speed will be increased even for the same stamping part. Thus, the end velocity of the pre-acceleration of the die cushion is set according to the drawing stroke and SPM. Therefore, the parameters of the pre-acceleration stage, which need to be set in this study, are the torque and the time point starting the pre-acceleration, which is determined by the time duration of the pre-acceleration stage and the time point starting the drawing stage.

If the die cushion is made by a power screw having a lead (L) driven by a servo motor, which has an equivalent total moment of inertia (JΣ) of the mechanical system of the servo cushion to drive, the nut or the cushion pad attached to the power screw has a linear acceleration (a) under a motor torque (T) to the whole mechanical system having an ideal efficiency (η):

\[ a = \eta \frac{L}{2\pi J_\Sigma} T \]  \hspace{1cm} (1)

while the cushion pad has a linear velocity (v) by integrating equation (1) with time

\[ v = \eta \frac{L}{2\pi J_\Sigma} t T \]  \hspace{1cm} (2)

which is proportional to the torque and the time duration, and a linear stroke (s),

\[ s = \frac{1}{2} \eta \frac{L}{2\pi J_\Sigma} t^2 \]  \hspace{1cm} (3)

which is proportional to the torque and square of the time duration. Thus, the torque (T) and time duration (t) for the pre-acceleration could be directly determined either with the end velocity (ν) of the pre-acceleration stage according to equation (2) or with the stroke (s) according to equation (3), respectively, once the efficiency η of the die cushion system is determined through experiments. To determine the efficiency η, one can give the servo motor a torque value T in the torque control mode to accelerate the cushion pad without any load on it, and record the velocity ν or the stroke or moving distance s for a time duration t. The η value can then be estimated by linear regression of the experiment data according to equation (2) or (3).
3. Experimental setup
For the above mentioned purpose, this study has established a servo mechanical die cushion as shown in figure 2 to verify the feasibility of pre-acceleration by applying torque control. The servo die cushion used for this research is based on the common single-acting mechanical press in the market, which is equipped with a rated capacity of 1,079 kN (110 tons) and a ram stroke of 110 mm. There is also a space of at least 500 mm high, 600 mm wide and 500 mm deep underneath the press bed for implementing the die cushion, which must have a 35 kN (3.6 tons) capacity and a stroke of 80 mm [11].

This servo die cushion includes servo motor, coupling, torque meter, gear box, pin pad, guide cylinders along with ball screw, and control unit. The servo cushion is equipped with a three-phase AC driver (S08-SMD-34A-3575-00, Syntec, Hsinchu, Taiwan), which drives a three-phase AC servo motor (TSB18113H-DB7A-D, Teco, Taipei, Taiwan) having an output of 11 kW with a torque 70 N·m at the rated speed 1500 rpm. The screw serves for the linear movement of the cushion pad and has a maximum stroke of 100 mm with a lead of 12 mm under a transmission ratio of the gear box in 1:2, so that a maximum blankholder force of 35 kN and a maximum linear velocity of 250 mm/s can be provided at the rated speed of the servo motor. The die cushion is controlled by a PC-based servo controller (21MA-H, Syntec, Hsinchu, Taiwan) providing an integrated development environment to edit programmable logic controller (PLC) ladder diagram along with machine state diagram (MSD) and assembly program for building up a human machine interface (HMI) customized panel boxes and buttons to input and to control the functions in each of the above mentioned stages: placement, pre-acceleration, drawing, holding, pickup, and lifting, including the mutually exclusive switch between velocity and torque control mode required for the die cushion system.

4. Results and discussions
Figures 3 and 4 are the response surface of the average velocity and the average stroke, respectively, measured at different time duration by using 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% of the rated torque of the servo motor, 70 N·m, respectively, as the torque command input to make the die cushion move without carrying any loads. It can be observed that the velocity shown in figure 3 does have a bilinear relationship with the torque $T$ and the time duration $t$ as described in equation (2), while the stroke shown in figure 4 is slightly linear with the torque $T$ and parabolic to the time duration $t$ as described in equation (3).
If the velocity and the stroke of the pin pad obtained in figures 3 and 4 under different servo motor torque settings but at the same time duration of 0.3 s are closely compared as shown in figure 5, it can be found that the apparent efficiencies (green line) for the velocity (solid line) and for the stroke (dash line) are not identical. The theoretical values (red line) shown in figure 5 are those calculated from equations (2) and (3) with the efficiency $\eta$ of the die cushion system as 1, in that the total moment of inertia $J_\Sigma$ of the whole die cushion relative to the servo motor shaft was calculated as 0.046 kg·m². The apparent efficiency is then calculated as the quotient of the experimental value (blue line) divided by its theoretical value. The difference of the apparent efficiencies for the velocity and the stroke might be attributed to the control scheme, which could have caused the output torque values of the servo motor to not be identical to the settings. Furthermore, the different friction characteristics from location to location between the screw and the nut might cause the different behavior of the die cushion under the action of different torques as well. Likewise, it can be observed that the apparent efficiency for the velocity or for the stroke is not a fixed value and changes with the torque input settings of the servo motor. The greater the torque input setting, the higher the velocity or the stroke of the die cushion and the greater the apparent efficiency of the system for the velocity and for the stroke.

Overall, the results of the velocity as well as the stroke on the input torque and the time duration can be modelled via linear regression, like equations (2) and (3). A relation

$$v = 5.012 T^{1.282} t^{0.930}$$  \hspace{1cm} (4)

would be obtained for the velocity and

$$s = 0.465 T^{1.397} t^{1.067}$$  \hspace{1cm} (5)

**Figure 3.** Velocity of the die cushion related to the applied torque and the time duration.

**Figure 4.** Stroke of the die cushion related to the applied torque and the time duration.

**Figure 5.** Velocity and stroke of the die cushion related to the applied torque at time 0.3 s obtained in theory and from experiment as well as their apparent efficiencies.
for the stroke. Even the torque and the time duration could be determined for a given velocity and a stroke of the pre-acceleration by directly solving equations (4) and (5). However, it might be a wrong solution because the exponents of the torque and the time duration shown in equations (4) and (5) deviate significantly from equations (2) and (3). Furthermore, using a constant efficiency to determine the torque and the time duration from equations (2) and (3) for the velocity and for the stroke seems to not be applicable to the experiment results as well. As shown in figure 5, due to the change in the output torque of the servo motor caused by the control scheme, the efficiency determined from experiments is not constant neither for all torque settings, nor for the velocity and for the stroke at an individual torque setting. However, if a close glimpse is taken at the efficiencies for the velocity and for the stroke, there still exists a linear relation between these efficiencies in each individual torque setting. Thus, if a linear regression is taken in each individual torque setting, an empirical model from the experiment results could be found as

\[ v = f(T)(t + t_0(T)) \]  \hspace{1cm} (6)

for the velocity and

\[ s = \frac{1}{2} f(T)(t + t_0(T))^2 + h(T) \]  \hspace{1cm} (7)

for the stroke. They are similar to equations (2) and (3) having a linear relation to the torque related function \( f(T) \) and a linear or parabolic relation to the time related function \( t + t_0(T) \), where \( t_0(T) \) means a time offset and \( h(T) \) means a jump imposed or induced by the torque setting. That means that the characteristics of the motion of the servo cushion still follow the rule as shown in equations (2) and (3), even there are some effects of the torque settings due to the control scheme as the functions \( t_0(T) \) and \( h(T) \) shown in equations (6) and (7).

Based on the finding as shown in figure 5 and in equations (6) and (7), the efficiency of the whole die cushion should be separately treated for the velocity response and for the stroke response as well as for each individual torque setting, even though the response of the velocity and of the stroke to the torque and the time duration are statistically high co-relative to each other. That means that the efficiency \( \eta \) in equations (2) and (3) should not be considered as identical but related to each other. Under this consideration, the torque and the time duration can be determined for the pre-acceleration stage for a given velocity and stroke by finding the intersection of the curve on the velocity response surface having the given velocity and the curve on the stroke response surface having the given stroke.

5. Design scheme and verification with an example

Based on the above mentioned observation that the efficiency of the velocity and of the stroke to the torque and the time duration is not identical but related to each other for each individual torque setting, a design scheme is proposed to determine the torque and the time duration for the pre-acceleration stage to a given velocity and stroke. When the parameters for the pre-acceleration are going to be worked out with the servo cushion of the above mentioned experiment setup, the drawing stroke should be set according to the height of the drawn workpiece first. The crank angle of the press for starting the drawing stroke is then determined. The stroke per minute of the press ram is set according to the complexity of the workpiece geometry, and thus the velocity of the cushion pad is determined. Once the preset pre-acceleration stroke is given, the torque and the time duration for the pre-acceleration stage are determined by finding the intersection on the response surfaces shown in figures 3 and 4 using interpolation. According to the crank angle of the press for starting the drawing stroke and the time duration for the pre-acceleration along with the stroke per minute of the press ram, the crank angle for starting the pre-acceleration can then be calculated, so that the PLC of the press controller can timely notify the die cushion to start pre-acceleration with the obtained torque setting registered in the PLC of the die cushion controller. After the pre-acceleration, the die cushion will push the press ram with the given blankholder force for the drawing stage.

To verify the feasibility of the aforementioned design scheme proposed by this research, an example is taken to determine the torque and the time duration for the pre-acceleration as follows.
Step 1: set the height of the drawing workpiece to 50 mm, with which the crank angle of the press is determined with the crank angle stroke chart of the press provided by the press maker, and set the stroke per minute of the press ram according to the geometric complexity of the workpiece, here 15 SPM, with which the final velocity of the pre-acceleration stage is determined along with the crank angle speed chart of the press as 119 mm/s.

Step 2: set the pre-acceleration stroke to 15 mm.

Step 3: determine the torque setting and the time duration for the pre-acceleration by finding the intersection on the response surfaces shown in figures 3 and 4 using interpolation with the velocity of 119 mm/s and the stroke of 15 mm, giving 33.8 N·m and 0.22 s, respectively.

Step 4: test the servo cushion by setting the values obtained in the above steps. Figure 6 shows the results recorded from the registers of the controller during the operation of the servo motor in step 4. The servo cushion is lifted from the pickup position (-72 mm, blue line) to its top dead center pad (0 mm) within 300 ms. The servo cushion starts in the motion control mode, so that its torque response (gray line) is random and the velocity has a trapezoidal profile as pre-defined with a constant acceleration and deceleration. Once the servo cushion is at its top dead center, all of its signals are staying still until the control mode is switched to the torque control and the command of the pre-acceleration is given at 1,276 ms, setting the torque to 33.8 N·m. After 220 ms, the torque is reset to 0. It can be observed that the die cushion has a position -14.93 mm and a velocity 119.6 mm/s at 1,496 ms. After that the velocity is decaying to 0 and the cushion stays at -14.93 mm, as the torque is reduced to 0.

![Figure 6](image-url)  
Figure 6. Test results of validation of pre-acceleration of the die cushion.

According to the results of the above verification, the deviation to the needed pre-acceleration velocity of the die cushion is 0.39%, and the deviation of the stroke is 1.55%. Both of them are within ±2.5%, which can be accepted for engineering applications. In contrast, as mentioned in the previous chapter, if the overall relations shown in equations (4) and (5) are taken to determine the parameters, the obtained values are 8.76 N·m for the torque and 1.51 s for the time duration, which is far away from the defined time interval (≤0.3 s) of the response surface and should not be accepted for this application. That means that the implied constant efficiency in equations (4) and (5) showing meaningless relation to the torque and the time duration is not adequate to this application.

6. Conclusion

This study has used a servo motor controller having only the mutually exclusive switching function between motion and force control in a servo mechanical die cushion to enable the cushion to possess a pre-acceleration function by force control. A design scheme needed to determine the setting parameters for the pre-acceleration of the die cushion is proposed in this study as well, in that the response surfaces of the velocity and the stroke of the die cushion to the torque setting and the execution time duration of the torque command are experimentally generated and interpolation is used to find the intersection of the response surfaces rather than to directly solve the surfaces described by linear regression. The proposed design scheme is verified by examples as well, which shows that the design scheme is indeed feasible regarding the deviation less than 2.5% to the designed velocity and stroke.
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