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Seven-bar mechanical press with hybrid-driven mechanism for deep drawing; Part 1: kinematics analysis and optimum design †

Hui Li* and Yuping Zhang

Department of Electromechanical Engineering, Shijiazhuang Institute of Railway Technology, Shijiazhuang 050041, P.R. China

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Abstract

The main feature of hybrid-driven linkage is the combination of the motion of a large constant velocity motor with that of a small servomotor via a two-degrees-of-freedom mechanism. Thereby, the hybrid-driven linkage can provide for programmable motion output. In the present study, a mechanical drawing press driven by a hybrid mechanism was optimized for displacement and velocity. An analysis of forward kinematics and an optimum model are presented. The actual displacement curves of the slider can approach the ideal ones by means of a two-step optimization. The dimensions of the linkage and the motion rules of the servomotor were optimized. The flexible features of the hybrid-driven drawing press are effectively demonstrated by three optimum examples. The optimum results validate the advantages of the hybrid-driven seven-bar mechanical press, such as its flexible slider speeds and adjustable strokes for drawing operations. By properly designing the input motion of the servomotor, the slider can pass through the desired trajectories.

Keywords: Hybrid-driven mechanism; Press; Deep drawing; Optimum design; Servomotor

1. Introduction

The metal forming press is among the most common of machines employed in manufacturing. The crank press incorporating a slider-crank linkage is unsuitable for deep drawing, owing to the fact that it lacks a constant working velocity [1]. In order to obtain constant working velocity, mechanical press manufacturers have developed multi-link presses. These innovations, specifically, have focused on increasing the approach and return velocities. To slow down the slider velocity in the working stroke, it is important to obtain constant working speeds or to make the load-stroke characteristics suitable for special applications. Multi-link presses, however, lack the flexibility required for different drawing technologies [2]. In order to achieve more suitable load-stroke characteristics, many researchers have developed a flexible press that uses a servomotor as the prime mover. Yan [3] utilized a servomotor as the power input for watt-type presses in order to improve the output motion characteristics. By properly designing the input speed, the output motion can pass through a desired trajectory. Yossifon and Shivpuri [4-6] also developed a servomotor-controlled mechanical press for precision forming. The force capabilities of servomotors, though, usually are limited. Recently, many researchers have shifted their attention to a hybrid-driven mechanism. The main idea behind the hybrid-driven linkage is the combination of the motion of a large constant velocity motor with that of a small servomotor via a two-degrees-of-freedom mechanism. The constant velocity motor provides the main power and motion requirements, while the servomotor acts as a low-power motion-modulation device. In this way, the hybrid-driven linkage can allow for programmable motion output. The idea of hybrid-driven linkage was initially studied by Tokuz and Jones [7-10]. They used a differential gearbox as the hybrid mechanism to drive a slider-crank linkage. The output rotation of the gear unit drove a slider-crank mechanism. The mechanism and motor elements were integrated into one coordinated system under computer control. The technical requirements for coordination and the means by which they were achieved are, in the relevant reports, discussed, and the results of experimental tests are presented. Also, a mathematical model of the system is presented, and the results of a computer simulation are compared with the experimental ones. On the basis of their data, Tokuz and Jones draw some important conclusions on this type of hybrid mechanism. Greenough and Brashaw [11] used a seven-bar mechanism as their hybrid linkage to generate a dwell motion. Their results show that the power requirement of the servomotor is minimal in comparison with that required to drive the load directly. Conner [12] synthesized a hybrid mechanism using a genetic algorithm. In his study, the peak

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*Corresponding author. Tel.: +86 311 88621089, Fax: +86 311 88621073
E-mail address: Huili68@163.com

power of the servomotor was reduced by approximately 70%. Kirecci and Dulger [13, 14] proposed a hybrid actuator, specifically, an arrangement consisting of a planar two-degrees-of-freedom, seven-link mechanism driven by a constant speed motor and a servomotor. They studied the dynamic behavior of their hybrid actuator by applying numerical simulations to the whole system. Further, Lagrangian mechanics were applied to derive equations of motion. The capability of the model, as developed with PID control action, was demonstrated on the basis of the simulation results. A hybrid actuator can save considerable amounts of energy when its mass moment of inertia is reduced to the required degree. The initial cost of the actuator depends on the power requirement of a given machine. The need for a higher power requirement will reduce the relative cost of the hybrid actuator when compared with direct servo drive systems. Herman [15] unveiled a hybrid cam mechanism. Such a mechanism adds much flexibility to the system, requiring only small peak power and peak torque from the servomotor. To achieve a same degree of flexibility in the dwell duration, the hybrid solution needs at least one order of magnitude less peak power from the servomotor than the servo solution. Seth and Vaddi [16-17] introduced the concept of programmable function generation. First, they studied a five-bar, two-DOF planar mechanism, which is the basis on which the simplest programmable function generator mechanisms can be synthesized. In the relevant reports, design considerations such as determinate kinematics and link dimensions, as well as coupler-point and control-input selection, are discussed. Second, Seth and Vaddi investigated a seven-bar translating-output programmable function generator. They present simulation results on minimization of the peak servo acceleration, the peak servo torque and the root mean square (RMS) servo torque, all of which suggest that significant reductions in the peak values of the selected variables are possible through optimized trajectories. Guo et al. [18, 19] studied trajectory planning for and optimization of a variable-speed servomotor-driven crank, by which, on the hybrid-driven servo press with the use of feedback control, different punch motions are realized. Li and Tso [20, 21] proposed an iterative learning control scheme for a hybrid-driven servo press applied to a stamping process. Li and Zhang [22, 23] investigated the overall feasibility of hybrid-driven mechanical presses, and introduced a scheme of a hybrid-driven nine-bar mechanical press for precision drawing, as optimized by a two-step process. They obtained the dimensions of the linkage and the motion rules for the servomotor. They found that by properly optimizing the displacement trajectory of the servomotor, the output motion of the slider can pass through the desired trajectories. This finding established that hybrid-driven mechanical presses have flexible output motion characteristics suitable for precision drawing.

The present paper presents a design method for dimensional synthesis of a hybrid-driven mechanical press suitable for deep drawing and for optimization of the displacement trajectory of the servomotor. The hybrid-driven mechanical press synthesized in this work has the characteristics of an approximately constant working velocity, having a quick return. By properly optimizing the displacement trajectory of the servomotor, the output motion of the slider can pass through the desired trajectories. Thereby, the hybrid-driven mechanical press can have flexible output motion characteristics suitable for deep drawing. These characteristics also provide advantages in applications to materials of different thickness or materials plastically deformed.

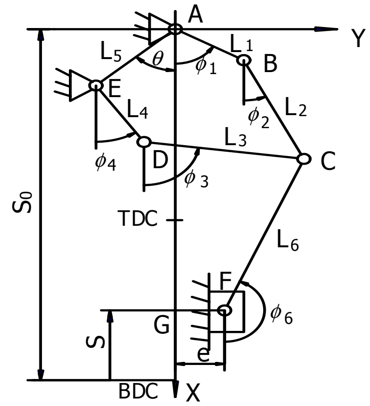


Fig. 1. Schematic representation of hybrid-driven press.

2. Forward kinematics analysis of hybrid-driven mechanical press

2.1 Mathematical model for seven-bar linkage

A hybrid-driven mechanical press, as shown in Fig. 1, is composed of a planar five-bar mechanism ABCDE and a dyad of CF. The lengths of links are denoted by L_1, L_2, L_3, L_4, L_5 and L_6. The crank L_1 is driven by a constant speed motor. The crank L_4 is driven by a servomotor. Link L_5 is the fixed link. The X-axis of the coordinate system in Fig. 1 is set in the vertical direction. The coordinate axes are fixed at point A. In order to improve the load characteristics of the slider, L_1, L_2 and L_6 are lined up in a straight line, as the BDC (Bottom Dead Center) of the slider. The beginning point of the displacement is taken as the BDC. The top dead center of the slider is the TDC.

According to Fig. 1, the loop vector equations are as follows:

$$\vec{L_1}+\vec{L_2}=\vec{AG}+\vec{GF}+\vec{L_6} \tag{1}$$

$$\vec{L_4}+\vec{L_3}=\vec{EG}+\vec{GF}+\vec{L_6}\ . \tag{2}$$

From Eqs. (1)-(2), the following additional equations are obtained:

$$L_1\cos\phi_1+L_2\cos\phi_2=(S_0-S)+L_6\cos\phi_6 \tag{3}$$

$$L_1\sin\phi_1+L_2\sin\phi_2=e+L_6\sin\phi_6 \tag{4}$$

$$L_4\cos\phi_4+L_3\cos\phi_3=(S_0-S-L_5\cos\theta)+L_6\cos\phi_6 \tag{5}$$

$$L_4 \sin\phi_4 + L_3 \sin\phi_3 = (L_5 \sin\theta + e) + L_6 \sin\phi_6 \quad (6)$$

where L_1, L_2, L_3, L_4, L_5, L_6, e, and θ are the dimension parameters of the mechanism, as shown in Fig. 1. S stands for the displacement function of the slider required by the deep drawing process. S_0 is given as

$$S_0 = \sqrt{(L_1 + L_2 + L_6)^2 - e^2} \ .$$

From Eqs. (3)-(6) we can obtain the function of the displacement of the slider with respect to the rotation angle ϕ_1 and ϕ_4 :

$$S = f(\phi_1, \phi_4) \ . \quad (7)$$

Therefore, the velocity $\dot{S}$ and the acceleration $\ddot{S}$ of the slider can be derived by continuously differentiating Eq. (7) with respect to time as follows:

$$\dot{S} = f_1(\phi_1, \omega_1, \phi_4, \omega_4) \quad (8)$$

$$\ddot{S} = f_2(\phi_1, \omega_1, \varepsilon_1, \phi_4, \omega_4, \varepsilon_4) \quad (9)$$

where ω_1 , ε_1 are the angular velocity and angular acceleration of link L_1 , and ω_4 , ε_4 are the angular velocity and angular acceleration of link L_4 .

3. Optimum design of hybrid-driven mechanical press

The optimization of a hybrid-driven mechanism includes determination of the objective function, the design variables, the constraints and the optimization method. Taking the widely used mechanical drawing press as an example, we will demonstrate the optimization of the hybrid-driven mechanical press [24].

3.1 Parameters of optimized hybrid-driven mechanical press

(1) The geometric parameters of the mechanism:

L_1, L_2, L_3, L_4, L_5, L_6, e, θ .

(2) The angular velocity ω_1 of the input link L_1 , which is driven by the constant velocity motor.
(3) The ideal displacement function S of the slider required by the deep drawing process:

$$S = S(t) = S(\phi_1, \phi_4) \ . \quad (10)$$

(4) Since the input link L_4 , which is driven by a servomotor, is a crank undergoing a circular rotation motion, we define the displacement trajectory of the link L_4 by a Bezier curve as follows:

$$\phi_4(t) = \sum_{i=0}^{n} x_i \times B_{i,n}(t) \qquad t \in [0,1] \quad . \quad (11)$$

Hence, the angular velocity and angular acceleration of the input link L_4 can be derived by continuously differentiating Eq. (11) with respect to time as follows:

$$\omega_4(t) = n\sum_{i=0}^{n-1}(x_{i+1} - x_i) \times B_{i,n-1}(t) \quad (12)$$

$$\varepsilon_4(t) = n(n-1)\sum_{i=0}^{n-2}(x_{i+2} - 2x_{i+1} + x_i) \times B_{i,n-2}(t) \quad (13)$$

Based on these parameters, we can obtain the displacement trajectory of input link L_4 by optimization.

3.2 Objective function

In order to realize the flexible output of the slider, the optimum design is carried out in two steps. The first step is to optimize the geometric parameters of the press (L_1, L_2, L_3, L_4, L_5, L_6, e, θ), on the assumption that the servomotor rotates at a constant angular velocity equal to that of the constant velocity motor. The second step is to optimize the displacement trajectory of the servomotor based on the results of the first step while keeping the geometric parameter unchanged. The ideal displacement function is marked as S^* , and the actual displacement function as *S*.

The objective function of the first step of the optimization is as follows:

$$f_{\mathrm{I}}(x) = W_1 f_1(x) + W_2 f_2(x) \ . \quad (14)$$

The objective function of the second step of the optimization is

$$f_{\mathrm{II}}(x) = W_3 f_3(x) + W_4 f_4(x) \quad (15)$$

where

$$f_1(x) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - S_i^*)^2} \ , \qquad f_2(x) = \sum_{i}^{6} L_i$$

$$f_3(x) = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(S_i - S_i^*)^2} \ , \quad f_4(x) = \sqrt{\frac{1}{N-m}\sum_{j=1}^{N-m}(S_j - S_j^*)^2}$$

in which N is the number of points considered in one cycle, m is the number of points in the working strokes, and W_1, W_2, W_3 and W_4 are the weighting factors.

3.3 Design variables

The design variables of the first step of the optimization are the geometric parameters of the linkage:

$[x]=[L_1, L_2, L_3, L_4, L_5, L_6, □, e]^T$.

In this design, a 10th order Bezier curve is used to represent the motion displacement of input link L_4. The motion curves of the input link L_4, Eqs. (11), (12) and (13), still contain undetermined control points:

$$x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_7, x_8, x_9, x_{10} .$$

Therefore, $x_0 = x_{BDC}$ and $x_{10} = x_{BDC} + 2\pi$ must be specified, and x_{BDC} is the corresponding crank angle when the slider is at the BDC. Hence, the design variables of the second step optimization are given as follows:

[x]= [$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_7, x_8, x_9$ **].**$^{\mathbf{T}}$

3.4 Constraints conditions

(1) In order to satisfy different motion trajectories of the slider, the input links L_1 and L_4 must make complete rotations. Li [22] completed his classifications of hybrid five-bar linkages. In this paper, the unrestrained double-crank type is used. The input links L_1 and L_4 are unrestrained cranks. Therefore, the inequality constraints are defined as follows:

$$\begin{cases} L_5 + L_1 + L_4 < L_2 + L_3 \\ L_2 + L_1 + L_4 < L_3 + L_5 \\ L_3 + L_1 + L_4 < L_2 + L_5 \end{cases} . \tag{16}$$

(2) In order to minimize the power required of the servomotor, the power distribution conditions should be satisfied [23]:

$$L_1 > \lambda \cdot L_4 \tag{17}$$

where λ is the power distribution coefficient, and $\lambda > 1$.

(3) To make the input link, L_4 rotates clockwise or anti-clockwise; the angular velocity of input link L_4 should be $\omega_4 > 0$ or $\omega_4 < 0$ at all times.

(4) Motion continuity of input link L_4

The motion continuity of Bezier curves is automatically satisfied at all points except at the boundary, where $t = 0$ and $t = 1$. Using Eqs. (12) and (13) for angular velocity and angular acceleration continuity, we have

$$C_1(\phi_1, ..., \phi_9) = \omega_4(0) - \omega_4(1) = 0 \tag{18}$$

$$C_2(\phi_1, ..., \phi_9) = \varepsilon_4(0) - \varepsilon_4(1) = 0 . \tag{19}$$

(5) Pressure angle condition: The pressure angle is significant as an indicator of good force and motion transmission. Therefore, it is reasonable to attempt to minimize the maximum pressure angle in a linkage design. The pressure angle inequality constraints is given as

$$\left|180° - |\phi_6|\right| \le [\alpha] \tag{20}$$

where $[\alpha]$ is the allowable pressure angle.

(6) Slider mobility condition: From Fig. 1 we know that the following inequality constraints should be satisfied:

$$L_6 > y_C - e \tag{21}$$

where y_C is the coordinate of point C in the y-direction.

(7) Link length condition: In order to have appropriate link lengths, we define the link lengths inequality constraints as follows:

$$L_{i\min} \le L_i \le L_{i\max} \qquad i = 1, 2, \cdots 6 . \tag{22}$$

3.5 Optimization results

The optimization of a hybrid-driven mechanical press obtains the geometric parameters of the mechanism and the displacement trajectory of the servomotor, according to the requirements of deep drawing processes. In the present study, we took a double-action drawing press, JA45-200, as a design prototype to demonstrate how to optimize a hybrid-driven mechanical press. This type of press is widely used in the metal-forming industry, especially in the drawing process. The specifications of the JA45-200 are given in Table 1. Fig. 2 shows the output motion of the press. The working stroke of the slider is about t=4.5s – 7.5 s. The stroke of the slider is 670 mm, and the maximum depth of drawing is about 315 mm. The maximum velocity of the slider shown in Fig. 2 in the

Table 1. Specifications of JA45-200.

Item	Specification
Nominal Capacity	3250kN
Main Motor Power	40kW (AC induction motor)
Nominal Capacity of inner slider	2000 kN
Nominal Stroke of inner slider	25 mm
Stroke of inner slider	670 mm
Max. Depth of drawing	315 mm
Strokes per minute	8 strokes/minute

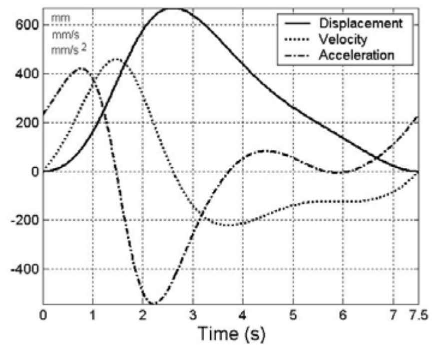
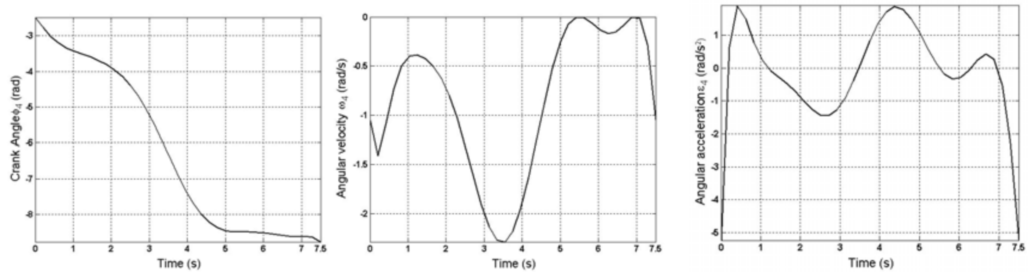
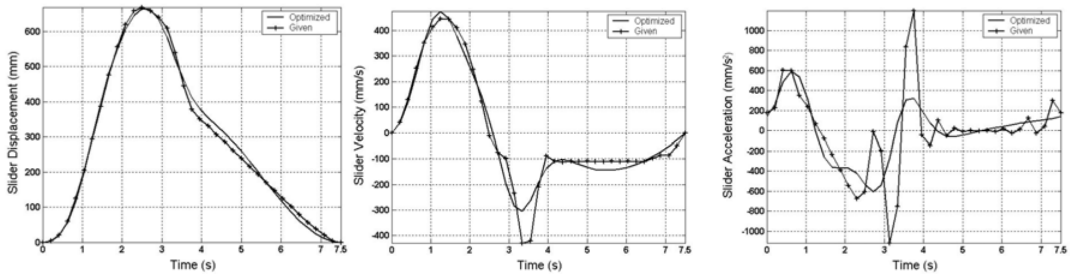


Fig. 2. Output motion of JA45-200 press.



(a) Input motion of crank L4



(b) Output motion of slider

Fig. 3. Optimal results for example 1.

working stroke is about 163.7 mm/s [24]. The maximum acceleration of the slider in the working stroke is approximately $0-210\,mm/s^2$.

The main objective of this research was firstly to optimize a hybrid-driven mechanical press, then to realize the output motion of the JA45-200 and to demonstrate the flexible features of the hybrid-driven drawing press. In order to generate the desired slider motion of a press, dimensional synthesis of these linkages is always important. Some specifications of slider motion often considered in syntheses are the position of the BDC, the working stroke length and the quick return property. Without exception, the optimum of the hybrid-driven seven-bar linkage requires a dimensional synthesis as well. In order to demonstrate the flexible feature of the hybrid-driven drawing press and to simplify the optimum program, the press was optimized by using the two-step optimum method. The geometric parameters of the press were optimized first, followed by the motion parameters. On this basis, and by properly optimizing the input motion of the servomotor, the various desired output motions were obtained [24]. The various flexible features of the hybrid-driven drawing press are illustrated in the following three examples.

(1) Example 1

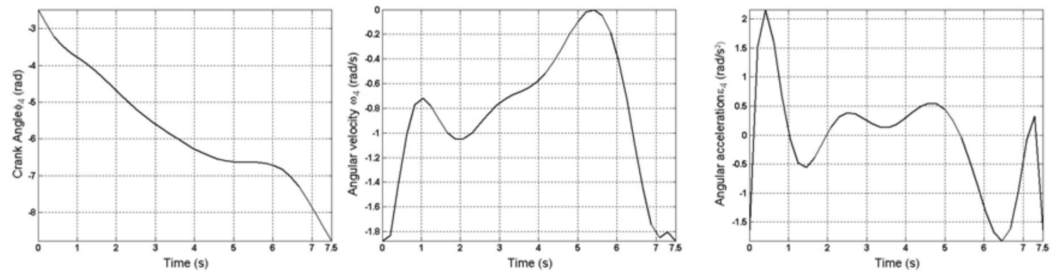
This example shows how to obtain aslider motion more suitable for deep drawing. The stroke of the slider and the stroke per minute were the same as for the JA45-200 press so as to compare their motion characteristics. According to the requirements mentioned above and the displacement curve of the slider given in Fig. 3, we can optimize the geometric parameters of the press in the first step using Matlab software. The optimal first-step results were obtained as follows:

L_1=161.089, L_2=674.046, L_3=673.62, L_4=114.166, L_5=509.678, L_6=1114.569, θ=-40.392 °, e=14.59.

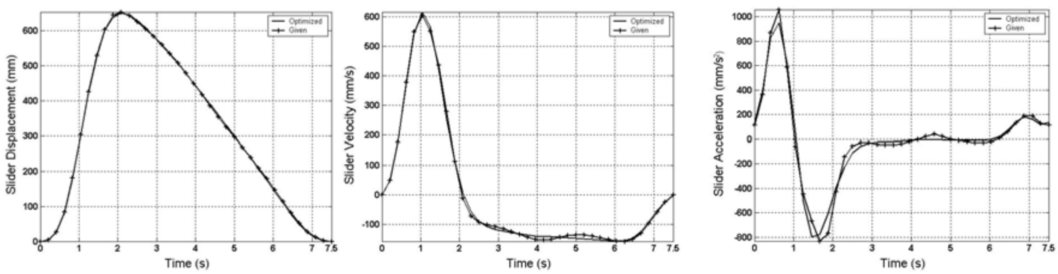
In the second step, the optimal results are obtained also by Matlab software. The corresponding input and output motion characteristics are shown in Fig. 3. The number of strokes per minute is 8 strokes/minute and the motion period is 7.5 seconds. The working stroke of the slider is t=4.5 s – 7.5 s approximately, and the maximum depth of drawing is about 315 mm. The maximum acceleration of the slider during the working stroke is about -50 mm/s^2 – 170 mm/s^2. Hence, by optimizing the slider's displacement trajectory as shown in Fig. 3, its velocity is steadier and more suitable for deep drawing during the working stroke of the slider. Compared with that shown in Fig. 2, the maximum velocity of the slider during the working stroke decreases from 163.7 mm/s to 135.83 mm/s. Therefore, a suitable drawing velocity for the deep drawing process can be obtained by properly optimizing the input motion of the servomotor.

(2) Example 2

In this example, the geometric parameters and the strokes per minute are the same as those in example 1. The aim of this example is to increase the maximum depth of drawing and change the characteristics of quick return. The optimum result is shown in Fig. 4. The working stroke of the slider is about t=3.2 s to 7.5 s, and the maximum depth of drawing is about 550 mm. The maximum acceleration of the slider shown in Fig. 4 during the working stroke is about -10 mm/s^2 – 190 mm/s^2. Comparing Fig. 4 with Fig. 2, the slider's velocity of the optimized press is steadier during the working stroke, and the maximum depth of drawing is longer. The maximum

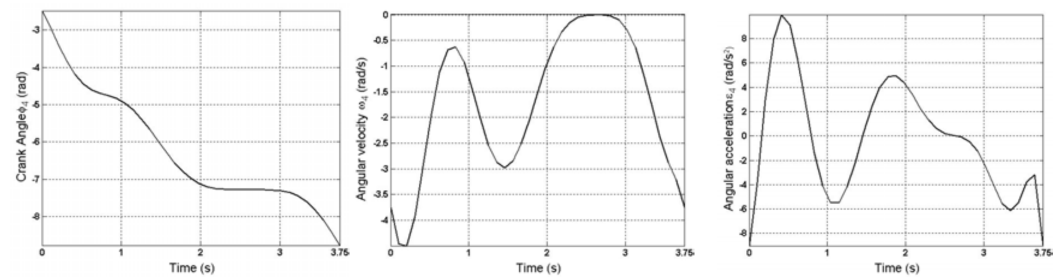


(a) Input motion of crank L4

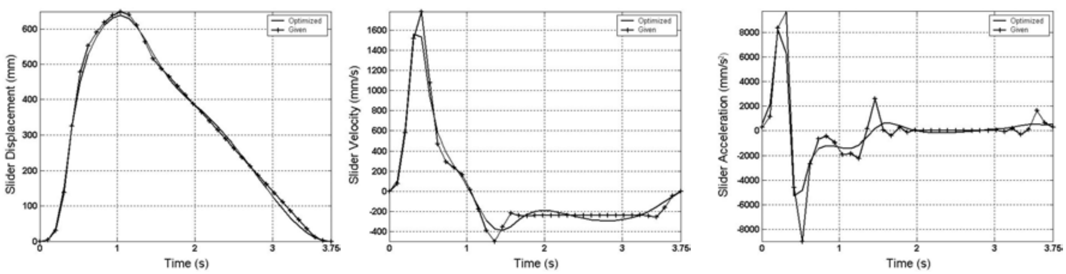


(b) Output motion of slider

Fig. 4. Optimal results for example 2.



(a) Input motion of crank L4



(b) Output motion of slider

Fig. 5. Optimal results for example 3.

working stroke can reach 550 mm, while the quick return time of the slider is shorter. Therefore, the various maximum depths of drawing and the quick return characteristic of this press are obtained by properly optimizing the input motion of the servomotor.

(3) Example 3

In this example, the geometric parameters are the same as in example 1, whereas the number of strokes per minute is 16 and the motion period is 3.75 seconds.

The optimum result is shown in Fig. 5. The working stroke of the slider is about t=2s to 3.75s, and the maximum depth of drawing is about 390 mm. The maximum acceleration of the slider during the working stroke is about 0 mm/s^2 – 180 mm/s^2. From example 3, the desired velocity trajectory of the slider during the working stroke was obtained. Also, the acceleration was steadier and the maximum depth of drawing was longer. Therefore, the advantage of the hybrid-driven mechanical press is that the number of strokes per minute may increase but the production qualities are maintained. This may improve the production rates greatly for the allowable slider velocity of the drawing process [25]. Again, the various figures for strokes per minute and the motion period of this press were obtained by properly optimizing the input motion of the servomotor.

The three examples showed that the various desired output motions of the slider can be obtained by properly optimizing the input motion of the servomotor. The flexible features of the hybrid-driven drawing press are effectively demonstrated by the above three examples.

4. Conclusions

This paper presents a novel concept for use of a hybrid-driven mechanism as a mechanical press is suitable for deep drawing. According to the requirements of the drawing process for a slider's motion characteristics, properly optimizing the input displacement of the servomotor, can make the output motion of the slider suitable for deep drawing. The following conclusions were derived from the present study:

(1) By correctly designing the input motion of the servomotor, we can not only obtain suitable output motion characteristics for deep drawing, but also make the slider pass through a group of more desired trajectories.
(2) By properly optimizing the input motion of the servomotor, we can obtain more suitable slider velocities, and by increasing the strokes per minute of the slider, we can obtain higher productivity.
(3) Because the slider can pass through different motion trajectories, different characteristics of quick return can be obtained for the hybrid-driven mechanical press.
(4) The structures of the press can be simplified, because there is no need to use a complex multi-bar mechanism to obtain the desired velocity characteristics of the slider.
(5) The percentage of finished products can be improved. Because of the low and constant slider velocity imparted by the hybrid-driven mechanical press, desired manufacturing conditions can be obtained. Even if low-quality materials are manufactured, the percentage of finished products can be high.

In short, by correctly designing the input motion of the servomotor, the hybrid-driven mechanical press can provide a programmable output motion. Thereby, with this kind of mechanical press, flexible output motion, higher load capabilities and higher production rates can be obtained, at lower costs.

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Hui Li received his B.S. in Mechanical Engineering from Hebei Polytechnic University, Hebei, China, in 1991. He received his M.S. in Mechanical Engineering from Harbin University of Science and Technology, Heilongjiang, China, in 1994, and his Ph.D. from Tianjin University's School of Mechanical Engineering, Tianjin, China, in 2003. He was a postdoctoral researcher at Shijiazhuang Mechanical Engineering College from August 2003 to September 2005, and at Beijing Jiaotong University from March 2006 to December 2008. He is currently a professor of Mechanical Engineering at Shijiazhuang Institute of Railway Technology, China. His research and teaching interests include hybrid-driven mechanisms, kinematics and dynamics of machinery, mechatronics, CAD/CAPP, and signal processing for machine health monitoring, diagnosis and prognosis. He is currently a senior member of the Chinese Society of Mechanical Engineering.