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What is This?

A case study of the five-point double-toggle mould clamping mechanism

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Abstract: This work attempts to enhance the performances of the stroke ratio and/or thrust saving of the conventional and Fanuc five-point double-toggle mould clamping mechanisms, at the cost of increasing the offset and varying the cross-head height and loosening the initial transmission performance within an acceptable extent, on condition that the overall horizontal length cannot exceed the one of the original design in the work of Lin and Hsiao [1]. In addition, to show the effect of the initial transmission performance and the effect of the combination of the offset and the crosshead height individually, the present and previous designs in the work of Lin and Hsiao without loosening the initial transmission performance are also presented. The parameter study in the work of Lin and Hsiao is extended to synthesize the conventional and Fanuc linkages and to find the optimal dimensions in the programming discrete domain. The kinematic stick diagrams in the open and closed positions for the original and present designs are shown, which may see some features of the profiles of the toggle linkages with the larger stroke ratio and/or thrust saving and the difference between the two designs.

Keywords: toggle clamping mechanism, injection-moulding machines

1 INTRODUCTION

The conventional five-point double-toggle mould clamping mechanism shown in Fig. 1 is used for small- to middle-sized injection-moulding machines [2]. Fanuc Japan Company Limited developed a new five-point double-toggle mould clamping mechanism shown in Fig. 2 [3]. In Figs 1 and 2, the upper portion above the centre line (CL) illustrates the mould closing state, whereas the lower portion below the CL illustrates the initial state. Constructions of the two types of mechanism are described in references [1, 2]. Let 1 to 8 shown in Figs 1 and 2 denote moving-platen side links (link 1), tailstock-platen side links (link 2), crosshead links (link 3), crosshead (4) shown in Fig. 3, tailstock platen (5), moving platen (6), tie bars (7), and stationary platen (8) in this work. Points A to E denote centres of pin joints.

Owing to the lengths of the tailstock-platen side links limited by the size (height) of the tailstock platen and the requirement of enough horizontal space for the ejector unit related with the lengths of the moving-platen side links, the lengths of the moving-platen side links are fairly greater than the ones of the tailstock-platen side links in the common designs of the conventional and Fanuc five-point double-toggle clamping mechanisms [4]. Such designs, e.g. the original design in reference [1] may have a quite good transmission characteristic. The initial thrust applied to the crosshead for the original design is 3.1 per cent of the original maximum thrust. If the initial transmission characteristic is poor (i.e. the initial thrust is too large), it may indicate that a quite high initial acceleration in the moving platen may cause vibration and noise,

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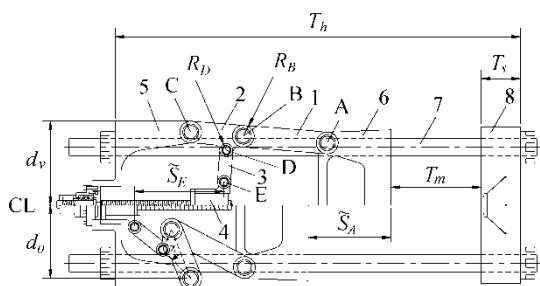
Fig. 1 Conventional five-point double-toggle mould clamping mechanism

Fig. 3 Crosshead for the two types of mechanism thrust by a ball nut-screw

especially for the faster mechanism. However, such an arrangement does not take full advantage of the five-point double-toggle clamping mechanism according to reference [1]. In reference [1], keeping the value of $(L_1 + L_2)$ (L_1 and L_2 are the distances between points A and B and points B and C, respectively) and the heights of the three sliders (the tailstock and moving platens and the crosshead) and the final orientation of the crosshead link invariable, a parameter study has been proposed to synthesize the conventional and Fanuc five-point toggle linkages and to find the optimal dimensions in the programming discrete domain. The parameter study has the advantage that the individual influence of the geometric parameters and the deeper understanding of the mechanism might be obtained. It has been concluded in reference [1] that the ratio of L_1 to L_2, whether for the conventional type or for the Fanuc type, should be as small as possible for thrust saving on condition that the geometry can be satisfied and the transmission characteristic can be accepted. Furthermore, the angle of swing of link 2 becomes smaller for the same opening stroke, so that the horizontal length of the projection (flange) of the tailstock platen may be reduced. If the horizontal space is not enough for the ejector unit, reference [1] adopts lengthening the projection of the moving platen. The variation of the overall
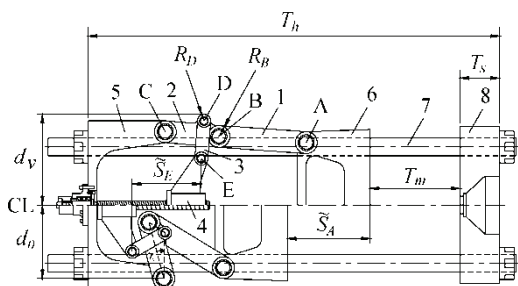
horizontal length of the mechanism may be acceptable.

However, in reference [1], the offset of joint C relative to joint A, the crosshead height and the height of joint A pinning the moving platen and the moving-platen side links are invariable. Such limitations may affect the ratio of L_1 to L_2 incapable of reduction due to the interference, especially for a larger stroke ratio case. In this study, the height of joint C may increase by modifying the tailstock platen. During the real mould clamping operation, only the upper and lower end portions of the moving platen are pressed strongly. In the case where a mould to be attached is small size, the moving platen may be curved; furthermore, this bending effect may affect the quality of moulding [3]. Accordingly, the height of the joint A will not be increased.

The aim of this work is to enhance the performances of the stroke ratio and/or thrust saving of the conventional and Fanuc five-point double-toggle mould clamping mechanisms, at the cost of increasing the offset of joint C and varying the crosshead height and loosening the initial thrust within 6 per cent of the original maximum thrust, on condition that the overall horizontal length cannot exceed the one of the original design in reference [1]. In addition, to show the effect of the initial transmission performance and the effect of the combination of the offset and the crosshead height individually, the present and previous designs in reference [1], without loosening the initial transmission performance, are also presented. In contrast with 3.1 per cent for the original design, the looseness in the initial transmission performance may be within an acceptable extent. For the enhancement of thrust saving, the input and output strokes are the same as the original ones in reference [1]. However, for the enhancement of the stroke ratio, the thrust should not exceed the original design. The parameter study in reference [1] is extended to synthesize the conventional and Fanuc five-point double-toggle linkages and to find the optimal dimensions.

Fig. 2 Fanuc five-point double-toggle mould clamping mechanism

2 INTERFERENCES

Figure 4 depicts a skeleton drawing for the lower half of the conventional five-point double-toggle mould clamping mechanism. The solid lines denote the position during the mould closing operation and the dashed lines denote the initial position. In Fig. 4, L_i ($i = 1–5$) are the distances between points A and B, B and C, D and E, C and D, and B and D, respectively; S_E and S_A are the displacements of the crosshead and the moving platen, respectively; h^0_{CE} is the horizontal distance between points C and E in the initial position. In this article, the symbol $(\tilde{\ })$ denotes that the quantity in parentheses is in the state of the final position of the mould closing operation. The superscript * is used only for the original mechanism.

The crosshead is thrust by means of a drive mechanism composed of a servo electric motor and a ball nut-screw or a hydraulic ram. In the present work, only the former is considered. The motor can acutate the screw shaft of the ball nut-screw to rotate to drive the crosshead locked on the nut of the ball nut-screw to move in the CL of the machine. The interference presented in reference [1] is only for the crosshead thrust by a hydraulic ram.

For the conventional five-point type, to prevent the interference between the toggle linkages and the screw shaft of the ball nut-screw, the following conditions with a minimum clearance of 5 mm should be satisfied

If $\alpha_0 + \gamma_C < \pi/2$, then check

$$
\begin{aligned}
&L_2 \sin \alpha_0 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 \sin(\alpha_0 + \gamma_C) + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{1}
$$

where R_B and R_D are the semi-widths of link 1 and link 3, respectively, and R_{bs} denotes the major radius of the screw shaft.
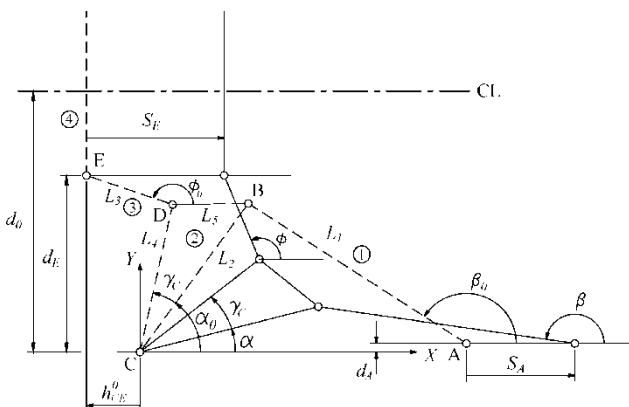

Fig. 4 Geometry of the conventional toggle linkage during mould closing

If $\alpha_0 < \pi/2$ and $\alpha_0 + \gamma_C \geqslant \pi/2$, then check

$$
\begin{aligned}
&L_2 \sin \alpha_0 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{2}
$$

If $\alpha_0 \geqslant \pi/2$, then check

$$
\begin{aligned}
&L_2 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{3}
$$

For the conventional five-point type, to prevent the interference between the crosshead and joint D in the initial position, the following condition with a minimum clearance of 5 mm should be satisfied

$$
L_3 \cos (\pi - \phi_0) \geq R_D + 5
\tag{4}
$$

For the Fanuc five-point type, to prevent the interference between the toggle linkages and the screw shaft of the ball nut-screw, the following conditions with a minimum clearance of 5 mm should be satisfied

If $\alpha_0 < \pi/2$, then check

$$
\begin{aligned}
&L_2 \sin \alpha_0 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 \sin(\alpha_0 - \gamma_C) + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{5}
$$

If $\alpha_0 \geqslant \pi/2$ and $\alpha_0 - \gamma_C < \pi/2$, then check

$$
\begin{aligned}
&L_2 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 \sin(\alpha_0 - \gamma_C) + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{6}
$$

If $\alpha_0 - \gamma_C \geqslant \pi/2$, then check

$$
\begin{aligned}
&L_2 + R_B \leqslant d_0 - R_{bs} - 5 \quad \text{and} \\
&L_4 + R_D \leqslant d_0 - R_{bs} - 5
\end{aligned}
\tag{7}
$$

For the Fanuc five-point type, to prevent the interference between the crosshead and joint B in the initial position, the following condition with a minimum clearance of 5 mm should be satisfied

$$
L_2 \cos \alpha_0 + h^0_{CE} \geq R_B + 5
\tag{8}
$$

The additional condition with a minimum clearance of 5 mm given subsequently for the Fanuc type should be satisfied to prevent the interference between joint D and the frame of machine

$$
L_3 \cos\left(\tilde{\phi} - \frac{\pi}{2}\right) + R_D \leqslant d_f + d_E - d_0 - 5
\tag{9}
$$

The following geometry conditions may be satisfied for the two types of mechanism

$$L_1 \geqslant 2R_B, \quad L_2 \geqslant 2R_B, \quad L_3 \geqslant 2R_D,$$
$$L_4 \geqslant R_B + R_D, \quad \text{and} \quad L_5 \geqslant R_B + R_D$$

$$(10)$$

3 OVERALL LENGTH OF THE MECHANISM

The following condition, with h_1 adopted as a standard to avoid the interference between the ejector unit and link 1, should be checked according to reference [1]

$$\Delta h_1 = h_{ejB} - h_1 \tag{11}$$

$$h_{ejB} = L_1 \sin \bar{\beta} - e_1^* \tag{12}$$

$$\bar{\beta} = \begin{cases} \beta_0 - \dfrac{\pi}{2} & \text{if } \alpha_0 < \dfrac{\pi}{2} \\ \cos^{-1}\left(\dfrac{L_2 - d_A}{L_1}\right) & \text{if } \alpha_0 \geqslant \dfrac{\pi}{2} \end{cases} \tag{13}$$

$$h_1 = L_1 \sin \bar{\beta} + (R_B + 5)\sec \bar{\beta}$$
$$- (d_0 - d_A - e_2)\tan \bar{\beta} \tag{14}$$

where h_{ejB} denotes the horizontal nearest distance between point B and the left end of the ejector unit; e_1 is the horizontal distance between point A and the left end of the ejector unit; e_2 is the vertical distance between the CL of the machine and the bottom end of the ejector unit; h_1 denotes the horizontal distance between point B and the left end of the ejector unit with a perpendicular clearance of 5 mm between the right side of link 1 and the left bottom end of the ejector unit.

In addition, the interference between the ejector unit and the screw shaft of the ball nut-screw in the initial position should be checked. Let h_{ejE}^0 denotes the horizontal distance between point E and the left end of the ejector unit in the initial position

$$h_{ejE}^0 = h_{AC}^0 + h_{CE}^0 - e_1^* \tag{15}$$

$$h_{AC}^0 = \sqrt{(L_1 + L_2)^2 - d_A^2} - \tilde{S}_A \tag{16}$$

where h_{AC}^0 is the horizontal distance between points A and C in the initial position. Let h_2 denote the horizontal distance between point E and the left end of the ejector unit in the initial position with a clearance of 5 mm between the ball nut-screw and the ejector unit. Then

$$h_2 = \tilde{S}_E + \tilde{h}_{bsE} + 5 \tag{17}$$

where $\tilde{h}_{bsE}$ is the horizontal distance between point E and the right end of the ball nut-screw in the final

position. The value of h_2 is adopted as a standard to avoid the interference between the ejector unit and the screw shaft of the ball nut-screw in the initial position. Then, check

$$\Delta h_2 = h_{ejE}^0 - h_2 \tag{18}$$

and

$$\Delta h = \min(\Delta h_1, \Delta h_2) \tag{19}$$

If the value of Δh is negative, the method of increasing the horizontal length of the projection of the moving platen by $-\Delta h$ is adopted.

Let Δh_{CE}^0 denote the difference between h_{CE}^0 and h_{CE}^{0*}, that is

$$\Delta h_{CE}^0 = h_{CE}^0 - h_{CE}^{0*} \tag{20}$$

If the value of Δh_{CE}^0 is negative, the horizontal length of the projection of the tailstock platen can be decreased by Δh_{CE}^0; however, the decrement should not exceed h_{CE}^{0*}. The variation of the overall horizontal length of the mechanism ΔT_h for the crosshead thrust by the ball nut-screw can be expressed as

$$\Delta T_h = \Delta h_{CE}^0 - \Delta h + \sqrt{(L_1 + L_2)^2 - d_A^2}$$
$$- \sqrt{(L_1^* + L_2^*)^2 - (d_A^*)^2} \tag{21}$$

The value of Δh is governed by Δh_2 for many conditions. For such situations, with the help of equations (15) to (18), (20), and (21), ΔT_h may be expressed as

$$\Delta T_h = \tilde{S}_A + \tilde{S}_E + e_1^* + \tilde{h}_{bsE} + 5 - h_{CE}^{0*}$$
$$- \sqrt{(L_1^* + L_2^*)^2 - (d_A^*)^2} \tag{22}$$

It may be seen from equation (22) that the input stroke should be reduced in order to increase the output stroke but without increasing the overall horizontal length of the mechanism.

4 INITIAL TRANSMISSION PERFORMANCE

Most of the injection-moulding machines have three-step to five-step adjustment for the mould closing speed. The initial thrust applied to the crosshead is 3.1 per cent of the necessary maximum thrust for the original mechanism with constant acceleration of 120 mm/s² in the crosshead to 0.5 s for the first stage of the mould closing process. To avoid unsound motion characteristic and consider the initial transmission characteristic for a fair comparison and

a further enhancement on thrust saving, the following conditions are demanded individually

$$a_A^0 > 0 \quad \text{and} \quad 0 < \frac{F_o^0}{F_{o,\max}^*} \leqslant 3.1\%$$

$$a_A^0 > 0 \quad \text{and} \quad 0 < \frac{F_o^0}{F_{o,\max}^*} \leqslant 6\%$$

(23)

where a_A^0 denotes the initial acceleration of the moving platen and F_o^0 denotes the initial thrust applied to the crosshead. The mass of the moving platen with the ejector unit and the moving mould is 220 kg. The static friction coefficients at the slider connection for both the moving platen and pin joints are 0.125. The circuit defect may be checked by performing the position analysis step by step from α_0 to $\tilde{\alpha}$ with the decrement one degree. If the solution does not exist during the position analysis, it may indicate that there is a circuit defect.

5 PARAMETRIC STUDY

A conventional five-point double-toggle mechanism used in an injection-moulding machine serves as the object of improvement in the parametric study. The geometric and material properties of the original mechanism are shown in Table 1.

Without changing the specifications of the mould clamping force and the ejector unit, the original allowable mould thickness, and the stationary mould platen for the object of improvement, let A_1, A_2, A_c, n_1, n_2, n_3, n_c, n_B, r_C, r_D, R_B, R_D, e_2, d_f, T_m, T_s (Figs 1 and 2) and $L_1 + L_2$ be invariable in the parametric study. For comparison, the final orientation of the crosshead link $\tilde{\phi} = 92°$ will be kept invariable. Moreover, the friction coefficient in the pin joints is assumed to be 0.1 and the final total deformational force of the tie bars $\tilde{F}_c = 539$ kN is considered.

Owing to the supported blocks underlying the platens and the steel bands fixed on the upper surface of the frame, there is a clearance between joint C (projection) and the upper surface of the frame.

Let a minimum clearance be 8 mm between joint C and the frame; thus, the maximum value of d_0 is 300 mm ($d_f - R_B - 8$). Let a minimum clearance be 6 mm between joint E and the crosshead, i.e. $d_0 - d_E - R_D - R_o \geqslant 6$ (see Fig. 3 for R_o). Thus, the maximum value of d_E is ($d_0 - 95$) mm. Let $\tilde{S}_A = \tilde{S}_A^*$ and $\tilde{S}_E = \tilde{S}_E^*$ (i.e. the stroke ratio $S_r = S_r^* = 0.84$) for the two types of mechanism for the thrust-saving case and $\tilde{S}_A = 1.2\tilde{S}_A^*$ and $\tilde{S}_E = 0.88\tilde{S}_E^*$ ($S_r = 1.364S_r^* = 1.14$) for the conventional five-point type and $\tilde{S}_A = 1.3\tilde{S}_A^*$ and $\tilde{S}_E = 0.8\tilde{S}_E^*$ ($S_r = 1.625S_r^* = 1.36$) for the Fanuc five-point type for the larger stroke ratio case. Also, let d_0 be 235–300 mm with an increment of 5 mm and the corresponding offset d_A be $d_0 - (d_0^* - d_A^*)$ and then let d_E vary from ($d_0 - 95$) to 80 mm with a decrement of 5 mm. For the previously mentioned cases, let L_1/L_2 be 1.7 to 0.6 with a decrement of 0.01 and then let the value of L_4/L_2 vary from 1.0 to 0.3 with a decrement of 0.01 to find the profiles of the toggle linkages of two types with the minimum value of $F_{o,\max}$ denoted by $F_{o,\max}^g$ in the larger stroke ratio and thrust-saving cases.

6 RESULTS

The geometric parameters and the initial thrust corresponding to $F_{o,\max}^g$ of the present and previous designs with $F_o^0/F_{o,\max}^* \leqslant 3.1\%$ and $F_o^0/F_{o,\max}^* \leqslant 6\%$ for the thrust-saving case and the larger stroke ratio case are shown in Tables 2 and 3, respectively. The previous result indicates that the value of the offset and the crosshead height are invariable. The effect of the combination of increasing the offset and varying the crosshead height may be seen from the comparison between the present and previous designs with $F_o^0/F_{o,\max}^* \leqslant 3.1\%$. In contrast, the effect of the initial transmission performance might be seen from the comparison between the present design with $F_o^0/F_{o,\max}^* \leqslant 3.1\%$ and $F_o^0/F_{o,\max}^* \leqslant 6\%$.

6.1 The thrust-saving case

The thrust $F_{o,\max}^g$ for the present design of the conventional type with $F_o^0/F_{o,\max}^* \leqslant 6\%$ can be declined by

Table 1 Geometric and material properties of the original mechanism

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
A_1	2184	d_v^*	277	L_2^*	164	R_{bs}	25
A_2	3276	e_1^*	47	L_3^*	70.04	R_B	42
A_c	2827	e_2	81	L_4^*	133.17	R_D	29
d_0^*	235	E_1, E_2	172	L_c^*	1250	R_9	60
d_A^*	5	E_c	204	n_1	6	$\tilde{S}_A^*$	180.67
d_{ch}^*	129	$\tilde{h}_{bsE}$	35	n_2, n_c	4	$\tilde{S}_E^*$	215.23
d_E^*	135	h_{CE}^{0*}	101.44	r_B, r_C	22.5	T_h^*	1250
d_f	350	L_1	231	r_D	15	γ_C^*	28.49

Units: A_1, A_2, and A_c in mm²; E_1, E_2, and E_c in GPa; the length and distance in mm.

Table 2 Geometric parameters corresponding to $F^g_{o,max}$ for the thrust-saving case

d_0	d_A	d_E	L_1/L_2	L_4/L_2	γ_C (°)	L_3	$F^g_{o,max}/F^*_{o,max}$ (%)	$F^0_o/F^*_{o,max}$ (%)	ΔT_h	Δd_v	d_{ch}
Conventional five-point type with $\tilde{S}_A = \tilde{S}^*_A$ and $\tilde{S}_E = \tilde{S}^*_E$ ($S_r = S^*_r = 0.84$)											
Original design											
235	5	135	1.41	0.81	28.49	70.04	100	3.1	0	0	129
Previous design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
235	5	135	1.33	0.82	24.21	76.44	94.72	3.0	−13.5	0	129
Present design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
265	35	155	0.97	0.99	20.52	69.27	88.25	3.1	−13.5	30	139
Previous design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
235	5	135	1.33	0.82	24.21	76.44	94.72	3.0	−13.5	0	129
Present design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
275	45	180	0.73	0.68	1.19	159.20	74.13	5.9	−13.5	40	124
Fanuc five-point type with $\tilde{S}_A = \tilde{S}^*_A$ and $\tilde{S}_E = \tilde{S}^*_E$ ($S_r = S^*_r = 0.84$)											
Previous design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
235	5	135	1.54	0.87	36.21	213.67	72.54	3.1	−13.5	65.5	129
Present design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
235	5	110	1.54	1.0	30.45	187.22	69.58	3.1	−13.5	64.1	154
Previous design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
235	5	135	1.28	0.89	31.46	213.92	67.50	3.9	−13.5	65.8	129
Previous design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
245	15	135	1.02	0.90	25.92	205.98	64.23	5.1	−13.5	67.9	139

$L_1 + L_2 = 395$ mm, $\tilde{F}_c = 539$ kN, $F^*_{o,max} = 16$ kN, $T^*_h = 1250$ mm, $d^*_v = 277$ mm.

26 per cent when compared with the original design. The enhancement on the thrust saving is quite significant at the cost of the initial thrust rising from 3.1 to 5.9 per cent of the original maximum thrust and the height of the linkage above CL increasing by 40 mm. The results for the previous design of the conventional type with $F^0_o/F^*_{o,max} \leqslant 3.1\%$ and $F^0_o/F^*_{o,max} \leqslant 6\%$ are the same. The thrust $F^g_{o,max}$ for the present design of the conventional type with $F^0_o/F^*_{o,max} \leqslant 6\%$ can be declined by 21 per cent of $F^*_{o,max}$ when compared with the previous design of the conventional type with $F^0_o/F^*_{o,max} \leqslant 3.1\%$, where the amount of 7 per cent results from the effect of the combination of the offset and the crosshead height and the amount of 14 per cent are mainly from the effect of loosening the initial transmission performance.

The thrust $F^g_{o,max}$ for the present design of the Fanuc type with $F^0_o/F^*_{o,max} \leqslant 6\%$ can be declined by 8 per cent of $F^*_{o,max}$ when compared with the previous design of the Fanuc type with $F^0_o/F^*_{o,max} \leqslant 3.1\%$, where the amount of 3 per cent results from

Table 3 Geometric parameters corresponding to $F^g_{o,max}$ for the larger stroke ratio case

d_0	d_A	d_E	L_1/L_2	L_4/L_2	γ_C (°)	L_3	$F^g_{o,max}/F^*_{o,max}$ (%)	$F^0_o/F^*_{o,max}$ (%)	ΔT_h	Δd_v	d_{ch}
Conventional five-point type with $\tilde{S}_A = 1.2\tilde{S}^*_A$ and $\tilde{S}_E = 0.88\tilde{S}^*_E$ ($S_r = 1.36S^*_r = 1.14$)											
Previous design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
No solution can satisfy the interference condition or the initial transmission performance, and so on											
Present design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
No solution can satisfy the interference condition or the initial transmission performance, and so on											
Previous design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
The result has the necessary maximum thrust exceeding the original one by 2.29 per cent											
Present design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
270	40	120	0.88	0.66	0.05	105.90	94.21	5.7	−3.2	35	179
Fanuc five-point type with $\tilde{S}_A = 1.3\tilde{S}^*_A$ and $\tilde{S}_E = 0.8\tilde{S}^*_E$ ($S_r = 1.63S^*_r = 1.36$)											
Previous design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
The result has the necessary maximum thrust exceeding the original one by 22.39 per cent											
Present design with $F^0_o/F^*_{o,max} \leqslant 3.1\%$											
The result has the necessary maximum thrust exceeding the original one by 3.57 per cent											
Previous design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
The result has the necessary maximum thrust exceeding the original one by 11.25 per cent											
Present design with $F^0_o/F^*_{o,max} \leqslant 6\%$											
265	35	80	1.02	0.76	20.34	119.17	91.62	5.7	−2.4	56.1	214

$L_1 + L_2 = 395$ mm, $\tilde{F}_c = 539$ kN, $F^*_{o,max} = 16$ kN, $T^*_h = 1250$ mm, $d^*_v = 277$ mm.

the effect of the combination of the offset and the crosshead height and the amount of 5 per cent may be regarded as the effect of loosening the initial transmission performance.

For the present design with $F_{\mathrm{o}}^0/F_{\mathrm{o,max}}^* \leqslant 3.1\%$, the thrust $F_{\mathrm{o,max}}^g$ for the Fanuc type is 19 per cent of $F_{\mathrm{o,max}}^*$ less than the one for the conventional type, whereas the height of the linkage above CL for the former increases by 34 mm when compared with the latter. Moreover, for the present design with $F_{\mathrm{o}}^0/F_{\mathrm{o,max}}^* \leqslant 6\%$, the thrust $F_{\mathrm{o,max}}^g$ for the Fanuc type is 10 per cent of $F_{\mathrm{o,max}}^*$ less than the one for the conventional type, whereas the height of the linkage above CL for the former increases by 28 mm when compared with the latter.

For the present design with $F_{\mathrm{o}}^0/F_{\mathrm{o,max}}^* \leqslant 6\%$, the offset increases from 5 to 45 mm and the semi-height of the crosshead decreases from 129 to 124 mm for the conventional type, whereas the offset increases from 5 to 15 mm and the semi-height of the crosshead increases from 129 to 139 mm for the Fanuc type. Moreover, $\Delta h_{\mathrm{CE}}^0 = -34.5$ mm and $\Delta h = -23.5$ mm for the conventional type, whereas $\Delta h_{\mathrm{CE}}^0 = -40.1$ mm and $\Delta h = -26.9$ mm for the Fanuc type. The kinematic diagrams in the open and closed positions for the present designs with $F_{\mathrm{o}}^0/F_{\mathrm{o,max}}^* \leqslant 6\%$ and the original design are shown in Fig. 5.

6.2 The larger stroke ratio case

The present design of the conventional five-point type with $F_{\mathrm{o}}^0/F_{\mathrm{o,max}}^* \leqslant 6\%$ enables the original stroke ratio to increase by 36 per cent and the necessary maximum to decrease by 6 per cent at the cost of the initial thrust rising from 3.1 to 5.7 per cent of the original maximum thrust and the height of the
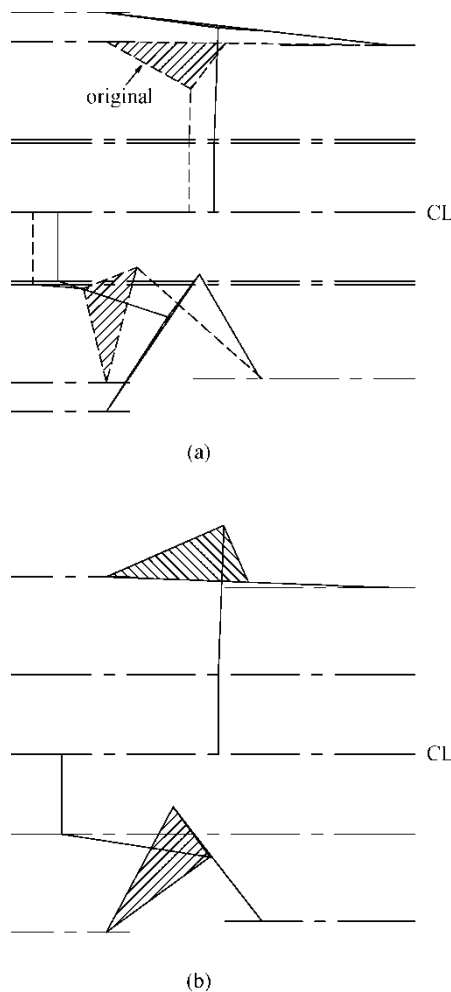

(a)

(b)

Fig. 5 Kinematic stick diagrams in the open and closed positions for the thrust-saving case: (a) the original and present designs of the conventional type and (b) the present design of the Fanuc type
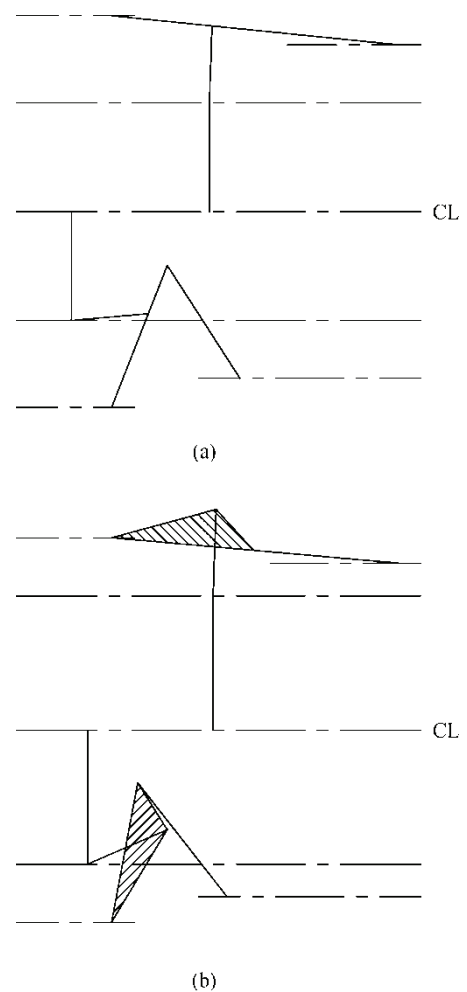

(a)

(b)

Fig. 6 Kinematic stick diagrams in the open and closed positions for the larger stroke ratio case: (a) the present design of the conventional type and (b) the present design of the Fanuc type

linkage above CL increasing by 35 mm. In contrast, the present design of the Fanuc five-point type $F_o^0/F_{o,max}^* \leqslant 6\%$ enables the original stroke ratio to increase by 63 per cent and the necessary maximum to decrease by 8 per cent at the cost of the initial thrust rising from 3 to 6 per cent of the original maximum thrust and the height of the linkage above CL increasing by 56 mm.

For the present design with $F_o^0/F_{o,max}^* \leqslant 6\%$, the offset and the semi-height of the crosshead increase by 35 and 50 mm for the conventional type and by 30 and 85 mm for the Fanuc type when compared with the original design. Moreover, $\Delta h_{CE}^0 = -46.3\,\text{mm}$ and $\Delta h = -45.1\,\text{mm}$ for the conventional type, whereas $\Delta h_{CE}^0 = -68.5\,\text{mm}$ and $\Delta h = -67.6\,\text{mm}$ for the Fanuc type. The kinematic diagrams in the open and closed positions for the present designs with $F_o^0/F_{o,max}^* \leqslant 6\%$ are shown in Fig. 6.

7 CONCLUSIONS

The present design for the conventional five-point type enables the original maximum thrust to reduce by 26 per cent without changing the input and output strokes and increasing the overall horizontal length at the cost of the initial thrust rising from 3.1 to 5.9 per cent of the original maximum thrust and the height of the linkage above CL increasing by 40 mm. However, the present design for the Fanuc five-point type enables the original maximum thrust to reduce by 36 per cent without changing the input and output strokes and increasing the overall horizontal length at the cost of the initial thrust rising from 3.1 to 5.1 per cent of the original maximum thrust and the height of the linkage above CL increasing by 68 mm. The present designs for the conventional and Fanuc types enable the stroke ratio to increase by 36 and 63 per cent of the original one and the thrust to decrease by 6 and 8 per cent, respectively, at the cost of the initial thrust rising from 3.1 to 5.7 per cent of the original maximum thrust and the height of the linkage above CL increasing by 35 and 56 mm, respectively. The Fanuc five-point type is superior to the conventional five-point type because of its thrust saving and the larger stroke ratio but at the cost of the linkage height.

In the original or common design, the length of link 1 is fairly greater than the one of link 2, and the horizontal length of the projection of the tailstock platen is quite large. In addition, the length of link 3 is quite smaller than the one of link 1 or link 2. The original or common design has a quite good initial transmission performance, but does not make the best of the mechanical advantage of the toggle clamping mechanism. If the quite large output stroke is the objective of design and the overall horizontal length of the mechanism is limited, the input stroke should decrease as shown in this work, thus probably resulting in a large increase in the thrust. In this work, at the cost of loosening the initial transmission performance within an acceptable extent and increasing the offset and varying the crosshead height, the ratio of L_1 to L_2 can reduce and the performances of the larger stroke ratio and/or thrust saving can enhance. The parameter study can find the suitable heights of joint C and the crosshead, where the ratio of L_1 to L_2 can reduce to a suitable one and the combinative arrangement of the ratio of L_4 to L_2 and the value of L_3 can make the mechanical advantage maximum. There are several marked features of the present linkages when compared with the original one stated as follows.

1. The ratios of L_1 to L_2 are smaller than the one for the conventional type and close to the one for the Fanuc type.
2. The horizontal length of the projection of the tailstock platen decreases and the corresponding one of the moving platen increases.
3. For the conventional type, the values of γ_C approach to zero degree and the values of L_3 are quite greater than the one of the original design.
4. For the larger stroke ratio case, the values of $(d_0 - d_E)$ are fairly greater than the values of d_E and L_3, that is, the crosshead height should increase with increasing the stroke ratio.

The approach to find the optimal dimensions in this work may be classified as the exhaustive search algorithm. The combination of the double-toggle linkage synthesis and the genetic algorithm for the optimal dimensions may be a further work for more efficiency.

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APPENDIX

Notation

a_A	acceleration of the moving platen

A_1, A_2, A_c	cross-sectional areas of link 1, link 2, and the tie bar	$\tilde{h}_{bsE}$	distance between point E and the right end of the ball nut-screw in the final position
d_0	vertical distance between the CL of the machine and point C	h^0_{CE}	horizontal distance between points E and C in the initial position
d_A	vertical distance between points C and A		
d_{ch}	semi-height of the crosshead	h_{ejB}	horizontal nearest distance between point B and the left end of the ejector unit
d_E	vertical distance between points C and E		
d_f	vertical distance between the CL of the machine and the upper surface of the frame	h^0_{ejE}	horizontal distance between point E and the left end of the ejector unit in the initial position
d_v	height of the linkage above the CL of the machine		
e_1	horizontal distance between point A and the left end of the ejector unit	L_c	length of the tie bar under tension
e_2	vertical distance between the CL of the machine and the bottom end of the ejector unit	L_i $(i = 1\text{--}5)$	distances between points A and B, B and C, D and E, C and D, and B and D
E_1, E_2, E_c	Young's modulus of link 1, link 2, and the tie bar	n_c, n_i $(i = 1\text{--}2)$	number of the tie bar and member i
F_{cl}	clamping force	r_B, r_C, r_D	radii of pin joints B, C, and D
F_o	thrust applied to the crosshead	R_B, R_D	semi-widths of link 1 and link 3
F^0_o	initial thrust applied to the crosshead	R_o	dimension shown in Fig. 3
$F_{o,max}$	maximum value of the thrust F_o during the mould clamping process	S_A, S_E	displacements of the moving platen and the crosshead
$F^g_{o,max}$	minimum value of $F_{o,max}$ in the thrust saving or larger stroke ratio case	S_r	stroke ratio defined as the ratio of the output stroke to the input stroke
		T_h, T_m, T_s	dimensions defined in Figs 1 and 2
h_1	horizontal distance between point B and the left end of the ejector unit with a perpendicular clearance of 5 mm between the right side of link 1 and the left-bottom end of the ejector unit	$\alpha, \beta, \gamma_C, \phi$	angles defined in Fig. 4
		α_0	angle α in the initial position
		$\bar{\beta}$	angle defined in equation (13)
		Δd_v	$d_v - d^*_v$
		$\Delta h, \Delta h_1, \Delta h_2, \Delta h^0_{CE}$	parameters defined in equations (19), (11), (18), and (20)
h_2	horizontal distance between point E and the left end of the ejector unit in the initial position with a clearance of 5 mm between the ball nut-screw and the ejector unit	ΔT_h	$T_h - T^*_h$
		$()^0$	quantity in the state of the initial position of the mould closing process
		$(\tilde{\ })$	quantity in the state of the final position of the mould closing process
h^0_{AC}	horizontal distance between points A and C in the initial position	$(\ )^*$	quantity only for the original mechanism