ON THE HYBRID-DRIVEN LINKAGE MECHANISM WITH ONE INPUT CYCLE CORRESPONDING TO TWO OUTPUT CYCLES

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ABSTRACT

A hybrid-driven five-bar linkage mechanism with one input cycle corresponding to two output cycles is presented. The proposed linkage mechanism is driven by a constant-speed motor and a linear motor, respectively. The output link can generate two same required output cycles during a single input cycle, while the rotational input link rotates with a constant angular speed, and the linear input link follows a reciprocating motion along a specified linear guide fixed on the rotational input link. The configuration, displacement relationship between the input and output links, and conditions of mobility of this proposed mechanism were studied, and a kinematic analysis was performed. The selection of the instantaneous motion trajectory of the linear input link and an optimal dimensional synthesis are also described. An example is provided to verify the feasibility and effectiveness of this methodology.

Keywords: hybrid-driven mechanism; linkage mechanism; kinematic analysis; dimensional synthesis.

MÉCANISME DE LIAISON HYBRIDE ENTRAÎNÉ COMPORTANT UN CYCLE D'ENTRÉE CORRESPONDANT À DEUX CYCLES DE SORTIE

RÉSUMÉ

Un mécanisme de liaison hybride entraîné à cinq barres comportant un cycle d'entrée correspondant à deux cycles de sortie est présenté dans cet article. Un moteur à une vitesse constante ainsi qu'un moteur linaire les entraînent. La liaison de sortie peut générer les deux cycles de sorties requises durant un seul cycle d'entrée pendant que la liaison rotative d'entrée tourne à une vitesse angulaire constante, et que la liaison linéaire d'entrée suit un mouvement alternatif le long d'un guide linéaire spécifique sur la liaison d'entrée rotative. La configuration, la relation de déplacement entre les liaisons d'entrée et de sortie, et les conditions de mobilité du mécanisme proposé sont étudiées, et l'analyse cinématique est effectuée. La sélection instantanée de la trajectoire de mouvement de la liaison linéaire d'entrée et une synthèse optimale dimensionnelle est aussi décrite. Un exemple est fourni pour vérifier la faisabilité et l'efficacité de la méthodologie.

Mots-clés : mécanisme hybride entraîné; mécanisme de liaison; analyse cinématique; synthèse dimensionnelle.

1. INTRODUCTION

A planar 2 DOF mechanism driven by a constant-speed motor and a servomotor is defined as a hybrid-driven mechanism such as five-bar, seven-bar, and nine-bar linkage mechanisms. The constant-speed motor provides the main power and motion requirements and the servomotor contributes the regulation of the output motion. This configuration makes the output motion of mechanism programmable and energy efficient.

The concept of a hybrid-driven mechanism was first proposed by Tokuz and Jones [1]. They used a differential gearbox with a constant-speed motor and a servomotor to drive a slider crank mechanism for simulating motion of stamping press. A mathematic model was proposed for designing hybrid-driven mechanisms and validated by experiments. Herman et al. [2] presented a hybrid cam mechanism which is a combination of a servomotor, a constant velocity motor and a cam follower. This hybrid solution is particularly successful for motions involving high peak acceleration and adds flexibility at low cost of energy. Greenough et al. [3] redefined hybrid-driven mechanisms and used a flywheel coupled to the shaft of a constant-speed motor. Their research results demonstrated a servomotor power reduction of up to 70%. Kirecci and Dulger [4] proposed a synthesis method to create all potential candidate mechanisms for their hybrid-driven arrangement using an inversion method. Dulger et al. [5] presented a seven-bar linkage mechanism in which one of the links coupled with the lead screw was adjustable and driven by two servomotors. Their study included modeling, a kinematic analysis, and a dynamic simulation. Ouyang et al. [6] proposed a controller based on the sliding-mode control technique to compensate for the speed fluctuation in a constant-speed motor for hybrid-driven machine systems. Their experimental results demonstrated that the controller was asymptotically stable. Seth and Vaddi [7, 8] defined planar 2-DOF mechanisms, such as five-bar and seven-bar linkages with two rotational inputs, as programmable function generators. They discussed their design considerations, such as determinate kinematics, link dimensions, selection of the coupler point and control input, and avoiding mode singularities. Their simulation results showed that the peak of the servo acceleration and servo torque and the root mean squared (RMS) servo torque were reduced significantly compared with a cam mechanism with the same output requirements. Meng et al. [9] proposed a seven-bar mechanical press driven by a constant-speed motor and a servomotor. They performed an inverse kinematic analysis and optimum dimensional synthesis. The results of their design example demonstrated that the fluctuations and peak values of the velocity and acceleration of the servomotor were markedly reduced after the optimum synthesis. Du and Guo [10] and Guo et al. [11] designed a 2-DOF seven-bar linkage mechanism driven by a large constant-speed motor and a small servomotor. Their mechanism was flexible and energy efficient. Li and Tso [12] proposed an iterative learning control scheme for a hybrid-driven servo press and experimentally verified the expected improved pouch position errors and precision. Soong [13] proposed a design method for adjustable mechanical forming presses that have a length-adjustable link. Li and Zhang [14] proposed a two-step optimization process to design seven-bar and nine-bar hybrid-driven presses for precision drawing. The optimum link dimensions and motion trajectories of the servomotor were determined, and the mechanisms had programmable output motions, higher load capabilities, higher production rates, and lower costs.

Planar 2-DOF hybrid-driven linkage mechanisms with a rotational input and indirect linear input, such as the mechanisms proposed in [5, 13], are not common. Soong [15] proposed a new linkage mechanism with a rotational input and a direct linear input. By controlling the instantaneous position of linear input link while rotational input link rotates with a constant angular speed, the required exact paths can be generated during a cycle. However, mechanisms in which the output link can generate two required motion cycles while the input links completes a single motion cycle are not found in literature.

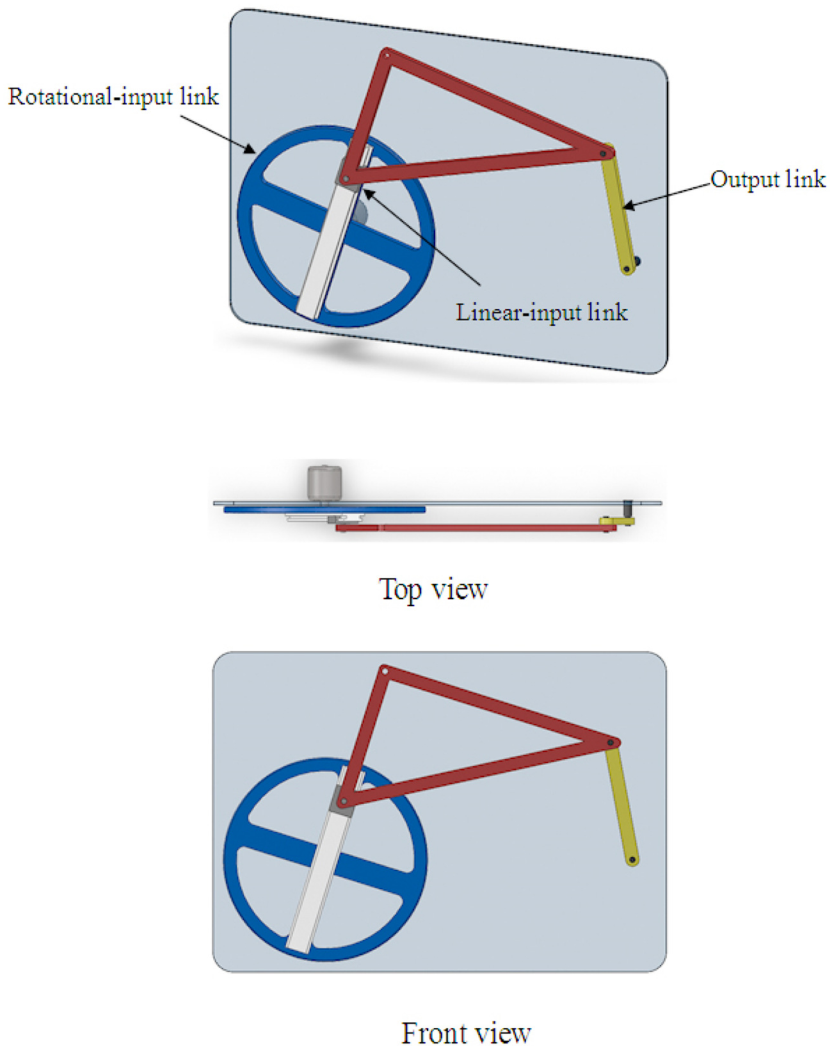

Fig. 1. Formation of the proposed mechanism [15].

2. NEW 2-DOF LINKAGE MECHANISM

The new 2-DOF linkage mechanism driven by a constant-speed motor and a linear motor is shown in Fig. 1 [15]. This is a five-bar linkage mechanism with a rotational input link and a linear input link. A wheel link driven by the constant-speed motor serves as the rotational input link, and a slider link driven by the linear motor fixed on the wheel link serves as the linear input link. The output link can generate two required motion cycles during a single input cycle, while the rotational input link rotates with a constant angular speed, and the linear input link follows a reciprocating motion along a specified linear guide fixed on the rotational input link.

3. POSITION RELATIONSHIP ANALYSIS FOR THE INPUT AND OUTPUT LINKS

A graphical position analysis for the input and output links is shown in Fig. 2. The analytical results verified the position relationships of one input cycle corresponding to two output cycles.

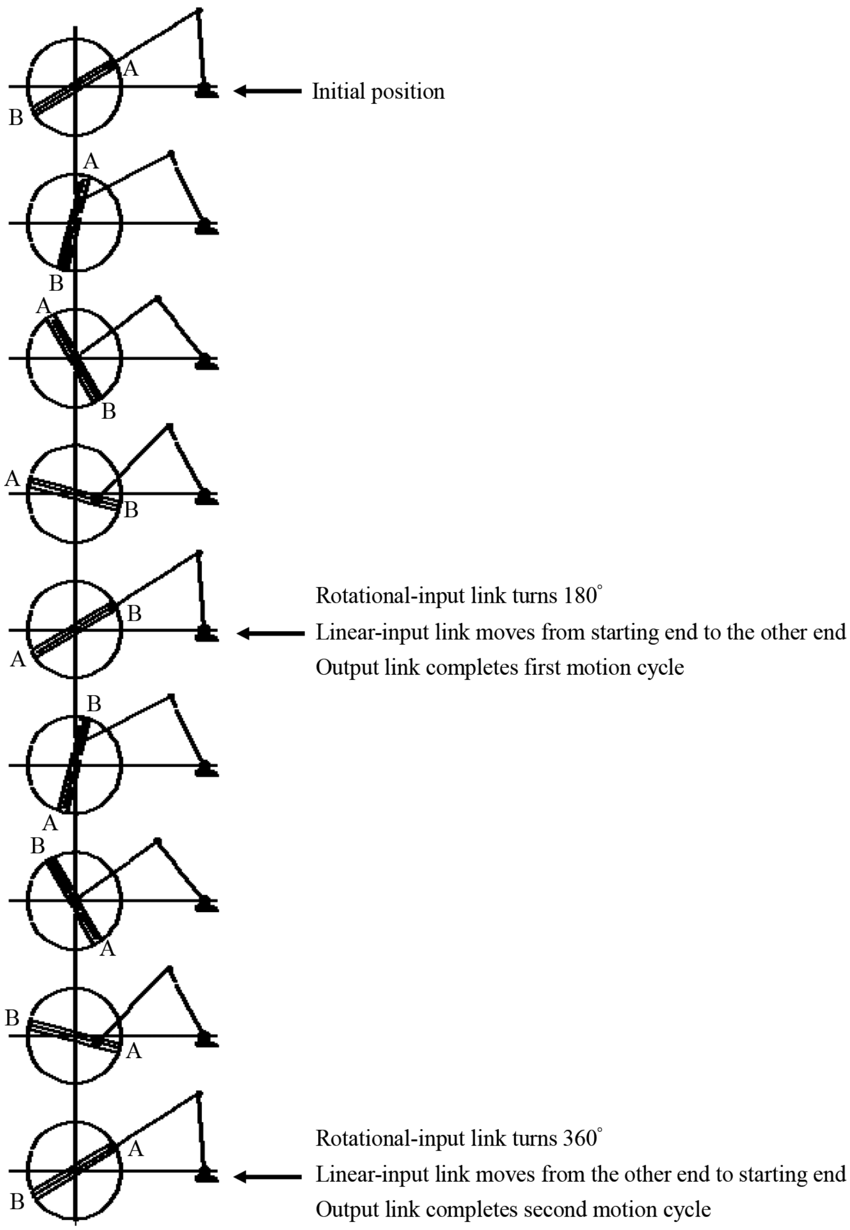

Fig. 2. The graphical position among input and output links.

4. MOBILITY OF THE HYBRID-DRIVEN MECHANISM

The coordinate system of the proposed 2-DOF hybrid-driven five-bar linkage mechanism is shown in Fig. 3. The lengths of links 1, 3, 4, and 5 (r_1, r_3, r_4, and r_5, respectively) are constant, whereas the instantaneous position relative to the center of the rotational input link, r_2, is variable. The proposed five-bar mechanism degenerates into a four-bar linkage when the linear input link is fixed. So it can be regarded as a four-bar linkage at any instantaneous moment during a cycle. Therefore, to guarantee that the rotational input link is a crank, the first condition is that the link length relationship among r_1, r_3, r_4, and r_2 has to satisfy Grashof's law. The second condition is that the shortest link length has to be r_1 or r_2 at any instantaneous moment during a cycle.

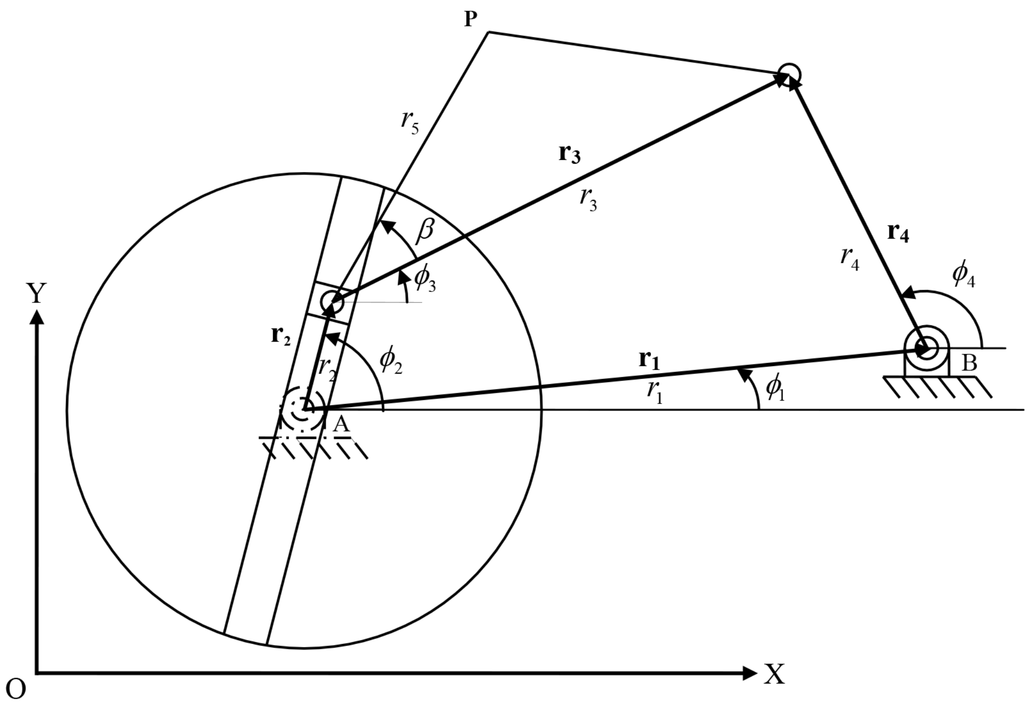

Fig. 3. The coordinate system of the proposed hybrid-driven mechanism.

5. KINEMATIC ANALYSIS

Figure 3 shows the coordinate system of the proposed 2-DOF hybrid-driven five-bar linkage mechanism. Points O, A, B, and P denote the origin of the coordinate system, two fixed pivots, and the coupler point of the mechanism, respectively. At any instantaneous moment during a cycle, the proposed mechanism can be regarded as a four-bar linkage with a variable link length, r_2. Therefore, the vector loop-closure equation is applied for the kinematic analysis. The angular positions of links 3 and 4, θ_3 and θ_4, can be expressed as follows:

$$\theta_4 = 2\tan^{-1}\left(\frac{-A \pm \sqrt{A^2+B^2-C}}{B+C}\right), \quad \theta_3 = 2\tan^{-1}\left(\frac{-D \pm \sqrt{D^2+E^2-F}}{E+F}\right), \tag{1}$$

where

$$A = 2r_4(r_2\sin\theta_2 - r_1\sin\theta_1), \quad B = 2r_4(r_2\cos\theta_2 - r_1\cos\theta_1),$$

$$C = -2r_1r_2(\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2) + r_1^2 + r_2^2 - r_3^2 + r_4^2,$$

$$D = 2r_3(r_1\sin\theta_1 - r_2\sin\theta_2), \quad E = 2r_3(r_1\cos\theta_1 - r_2\cos\theta_2),$$

and

$$F = -2r_1r_2(\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2) + r_1^2 + r_2^2 + r_3^2 - r_4^2.$$

Here, r_i and θ_i represent the link length and angular position of the i-th link, respectively. Therefore, the coordinates of the coupler point, p, can be written as

$$p_x = a_x + r_2\cos\theta_2 + r_5\cos(\theta_3+\beta), \quad p_y = a_y + r_2\sin\theta_2 + r_5\sin(\theta_3+\beta), \tag{2}$$

where a_x and a_y denote the coordinates of point A in the X and Y directions, respectively. The angular velocity of links 3 and 4, ω_3 and ω_4, can be obtained by differentiating Eq. (1) with respect to time,

$$\omega_3 = \frac{d\theta_3}{dt} = \frac{KJ - HL}{GJ - HI}, \omega_4 = \frac{d\theta_4}{dt} = \frac{GL - IK}{GJ - HI}, \tag{3}$$

where

$$G = -r_3 \sin\theta_3, \quad H = -r_4 \sin\theta_4, \quad I = r_3 \cos\theta_3, \quad J = -r_4 \cos\theta_4,$$
$$K = r_2 \sin\theta_2 \omega_2 - \frac{dr_2}{dt}\cos\theta_2, \quad L = -r_2 \cos\theta_2 \omega_2 - \frac{dr_2}{dt}\sin\theta_2.$$

The angular acceleration of links 3 and 4, α_3 and α_4, can be determined by differentiating Eq. (3) with respect to time,

$$\alpha_3 = \frac{d\omega_3}{dt} = \frac{JM - HN}{GJ - HI}, \quad \omega_4 = \frac{d\theta_4}{dt} = \frac{GL - IK}{GJ - HI}, \tag{4}$$

where

$$M = -\frac{d^2 r_2}{dt^2}\cos\theta_2 + 2\frac{dr_2}{dt}\sin\theta_2\omega_2 + r_2\cos\theta_2\omega_2^2 + r_2\sin\theta_2\alpha_2 + r_3\cos\theta_3\omega_3^2 - r_4\cos\theta_4\omega_4^2,$$
$$N = -\frac{d^2 r_2}{dt^2}\sin\theta_2 - 2\frac{dr_2}{dt}\cos\theta_2\omega_2 + r_2\sin\theta_2\omega_2^2 - r_2\cos\theta_2\alpha_2 - r_3\sin\theta_3\omega_3^2 + r_4\sin\theta_4\omega_4^2.$$

6. INSTANTANEOUS MOTION TRAJECTORY OF THE LINEAR INPUT LINK

According to the results of graphical displacement analysis of the input and output links in Section 3, the condition to generate a displacement relationship such that one input cycle corresponds to two output cycles is that the linear input link must follow a reciprocating motion along a specified linear guide fixed on the rotational input link while the rotational input link rotates with a constant angular speed during a cycle. Therefore, in this approach, the motion of the linear input link is designed to follow simple harmonic motion. The instantaneous position, velocity, and acceleration relative to the center of the rotational input link can be specified, respectively, as

$$r_2 = l_2\cos\theta_2, \quad \frac{dr_2}{dt} = -l_2\omega_2\sin\theta_2, \quad \frac{d^2r_2}{dt^2} = -l_2\omega_2^2\cos\theta_2 \tag{5}$$

where l_2 represents the radius of the rotational input link. Note that the position of the linear input link is at the start point C, as shown in Fig. 3, when $\theta_2 = 0°$.

7. OPTIMUM DESIGN

According to the results of the kinematic analysis, the design variables are a_x, a_y, r_1, l_2, r_3, r_4, r_5, θ_1, and β for the dimensional synthesis. An optimization procedure was used in this approach to determine all the design variables. The general optimization equations can be defined as follows:

$$\text{Minimize } f(a_x, a_y, r_1, l_2, r_3, r_4, r_5, \theta_1, \beta) = \sum_{i=1}^{n_i} w_i \,\text{obj}_i \tag{6}$$

subject to the constraints of equality and the constraints of inequality

$$c_j(a_x, a_y, r_1, l_2, r_3, r_4, r_5, \theta_1, \beta) = 0, \quad j = 1, \ldots, n_c,$$
$$g_k(a_x, a_y, r_1, l_2, r_3, r_4, r_5, \theta_1, \beta) < 0, \quad k = 1, \ldots, n_g, \tag{7}$$

where obj_i gives the objective functions, w_i gives the weighting factors, n_i gives the number of objective functions and weighting factors, c_i gives the constrained equality equations, g_i gives the constrained inequality equations, and n_c and n_g give the number of constrained equality and inequality equations, respectively.

Table 1. Dimensions of the reference four-bar linkage.

Parameter	r_1(cm)	l_2(cm)	r_3(cm)	r_4(cm)	r_5(cm)	θ_1 (°)	β (°)	a_x(cm)	a_y(cm)
value	22.2	20.6	23.3	30.6	0	–31	0	0	0

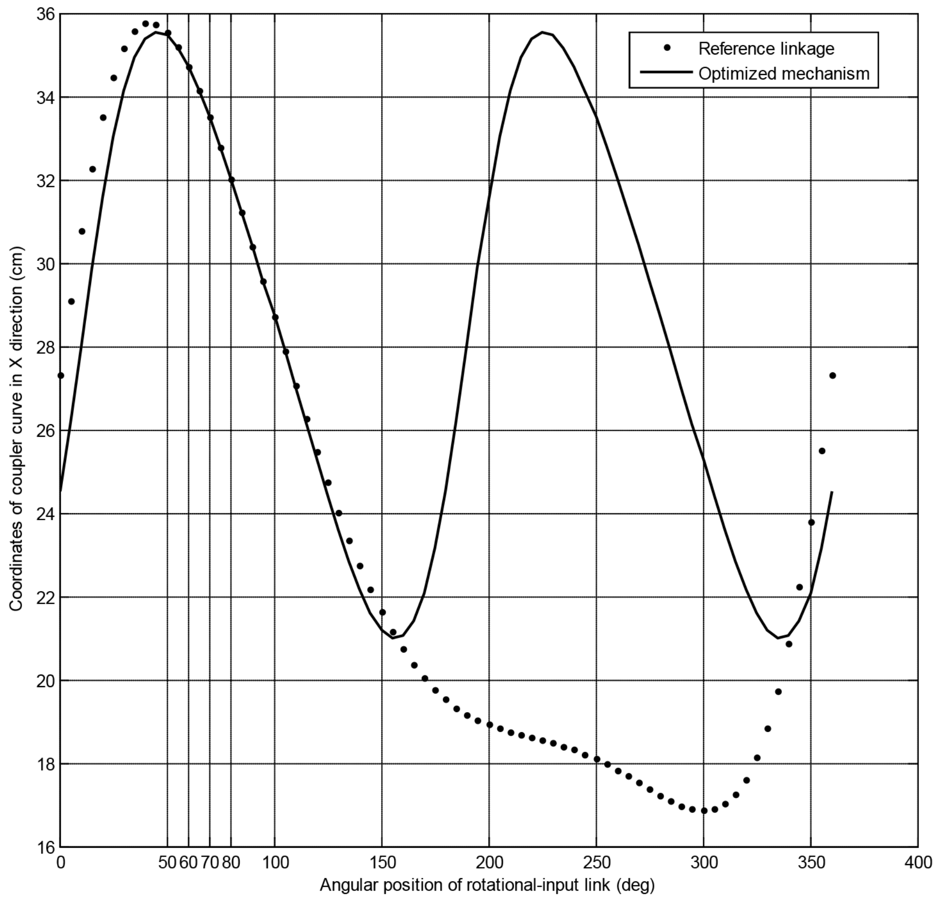

Fig. 4. The path coordinates of the coupler point in X direction for the example

8. DESIGN EXAMPLE

In the following example, we demonstrate how the proposed hybrid-driven five-bar linkage mechanism shown in Fig. 2 generates two same output cycles corresponding to one input cycle by controlling the motion of the linear input link, which follows simple harmonic motion while the rotational input link rotates at a constant speed during a cycle. The optimum dimension synthesis problem is solved by applying the "fmincon" function in the optimization toolbox of the Matlab software package.

In this example, we design the proposed hybrid-driven five-bar linkage mechanism to have the optimum transmission angle during a cycle, and so that its coupler point passes through three precision points at the same prescribed times as a reference four-bar linkage. The link dimensions of this reference four-bar linkage are shown in Table 1.

The objective function specified in Section 6 can be expressed as

$$\text{Minimize } f(a_x, a_y, r_1, l_2, r_3, r_4, r_5, \theta_1, \beta) = |90^\circ - \mu| \tag{8}$$

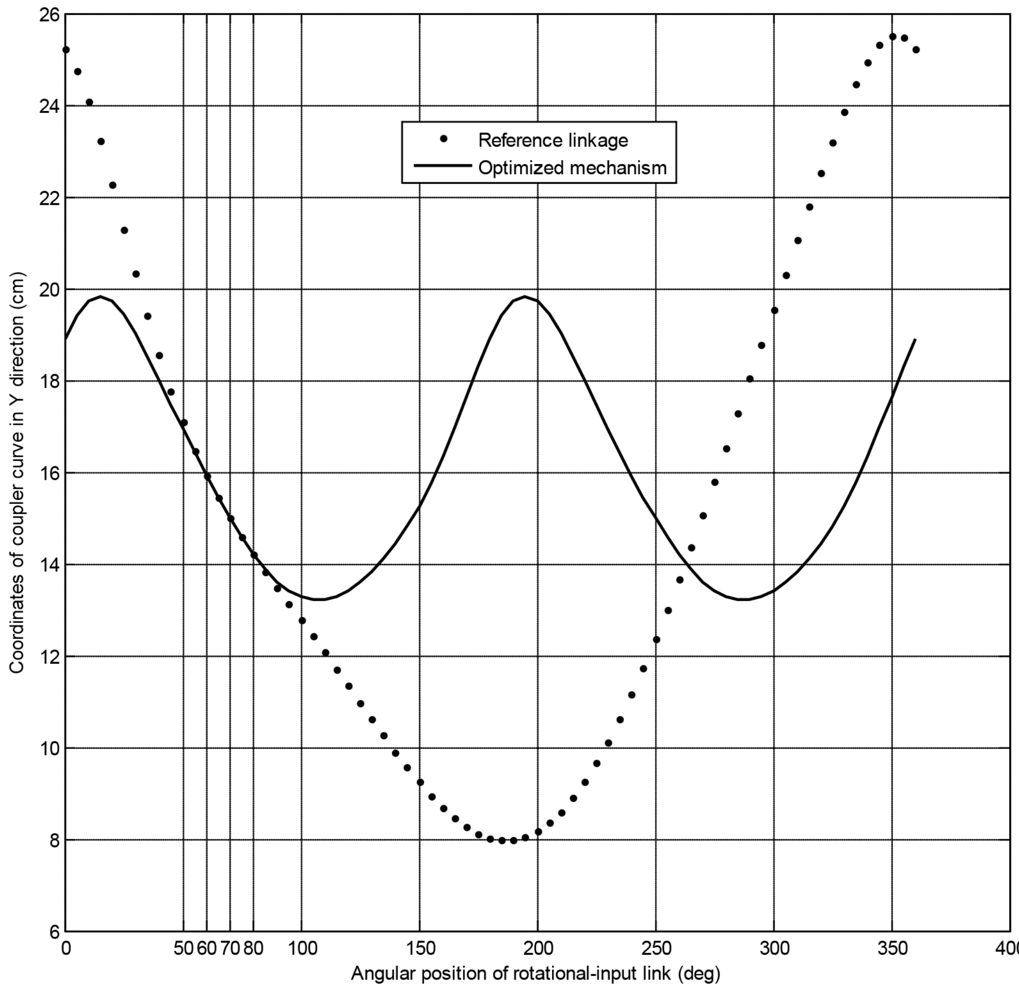

Fig. 5. The path coordinates of the coupler point in Y direction for the example.

subject to

$$
\begin{aligned}
&c_1(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{1x}(\theta_2 = 60^\circ) = 34.725,\\
&c_2(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{1y}(\theta_2 = 60^\circ) = 15.924,\\
&c_3(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{2x}(\theta_2 = 70^\circ) = 33.504,\\
&c_4(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{2y}(\theta_2 = 70^\circ) = 14.922,\\
&c_5(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{3x}(\theta_2 = 80^\circ) = 32.025,\\
&c_6(a_x,a_y,r_1,l_2,r_3,r_4,r_5,\theta_1,\beta) = p_{3y}(\theta_2 = 80^\circ) = 14.202, \qquad (9)\\
&g_1 = l_2\cos\theta_2 < r_1, \quad g_2 = l_2\cos\theta_2 < r_3, \quad g_3 = l_2\cos\theta_2 < r_4,\\
&g_4 = l_2\cos\theta_2 + L_l < L_m + L_n. \qquad (10)
\end{aligned}
$$

where μ is the transmission angle, L_l is the length of the longest link, and L_m and L_n are the link lengths between the shortest and the longest links, respectively.

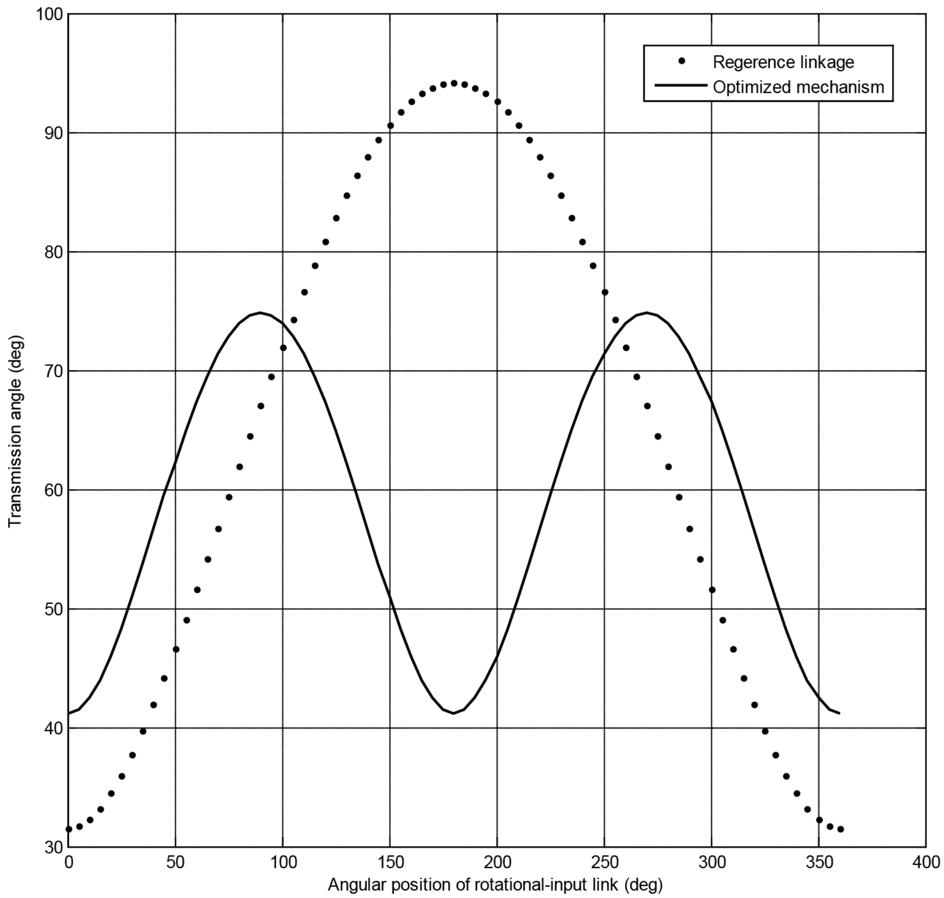

Fig. 6. The transmission angle for the example.

Table 2. The optimized kinematic dimensions for the desired mechanism.

Parameter	r_1(cm)	l_2(cm)	r_3(cm)	r_4(cm)	r_5(cm)	$\theta_1(\circ)$	$\beta(\circ)$	a_x(cm)	a_y(cm)
value	20.81	8.74	17.46	16.80	35.24	16.15	–10	11.39	–16.04

The coordinates of the precision points at various prescribed times are shown in Eq. (9). The optimized kinematic dimensions of the hybrid-driven five-bar linkage mechanism are shown in Table 2. The coordinates of the coupler curve in the X and Y directions and the optimized transmission angles during a cycle are shown in Figs. 4, 5, and 6, respectively.

The design results shown in Figs. 4 and 5 indicate that the proposed mechanisms generated two specified output cycles that had the same design requirements with the reference linkage for the example while the rotational input link rotated at a constant speed and that the linear input link followed simple harmonic motion during the cycle. The transmission angles were optimized in the example, as shown in Fig. 6. These results verified the feasibility and effectiveness of this methodology. Comparing with reference linkage, the proposed mechanism can easily generate two output motion cycles corresponding to one input cycle with more compact configuration and better transmission angles. Furthermore, the output link of this mechanism can be a slider or a link. By controlling the motion trajectories of linear input link, the desired output motion trajectories can be generated. Therefore, the proposed mechanism can be used to solve any path, motion or function generation problems.

9. CONCLUSIONS

A new 2-DOF hybrid-driven five-bar linkage mechanism with one input cycle corresponding to two output cycles was presented. The configuration, displacement relationship analysis among input and output links, and the conditions of mobility of this proposed mechanism were studied. A kinematic analysis was described. The selection of the instantaneous motion trajectory of the linear input link and the method of optimal dimensional synthesis were also discussed. An example was used to verify that for every cycle of the input links, the output link generated two same output motion cycles. The findings of this approach provide an important reference for future practical applications.

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REFERENCES

1. Tokuz, L.C. and Jones, J.R., *Hybrid Machine Modeling and Control*, Ph.D. Thesis, Liverpool Polytechnic, 1992.
2. Herman, J., Sraete, V.D. and Schutter, J.D., "Hybrid cam mechanism", *IEEE/ASME Transactions on Mechatronics*, Vol. 1, No. 4, pp. 284–289, 1996.
3. Greenough, J.D., Bradshaw, W.K., Gilmartin, M.J., Douglas, S.S. and Jones, J.R., "Design of hybrid machines", in *Proceedings of the Ninth World Conference on the Theory of Machines and Mechanisms*, Vol. 4, pp. 2501–2505, 1995.
4. Kirecci, A. and Dulger, L.C., "A study on a hybrid actuator", *Mechanism and Machine Theory*, Vol. 35, No. 8, pp. 1141-01149, 2000.
5. Dulger, L.C., Kirecci, A. and Topalbekiroglu, M., "Modeling and simulation of a hybrid actuator", *Mechanism and Machine Theory*, Vol. 38, No. 5, pp. 395–407, 2003.
6. Ouyang, P.R., Li, Q., Zhang, W.J. and Guo, L.S., "Design, modeling and control of a hybrid machine system", *Mechatronics*, Vol. 14, No. 10, pp. 1197–1217, 2004.
7. Seth, B. and Vaddi, S.S., "Programmable function generators-I: Base five-bar mechanism", *Mechanism and Machine Theory*, Vol. 38, No. 4, pp. 321–330, 2003.
8. Vaddi, S.S. and Seth, B., "Programmable function generators-II: Seven-bar translatory-output mechanism", *Mechanism and Machine Theory*, Vol. 38, No. 4, pp. 331–343, 2003.
9. Meng, C.F., Zhang, G., Lu, Y.H. and Shen, Z.G., "Optimal design and control of a novel press with an extra motor", *Mechanism and Machine Theory*, Vol. 39, No. 8, pp. 811–818, 2004.
10. Du, R. and Guo, W.Z., "The design of a new metal forming press with controllable mechanism", *Transaction of the ASME, Journal of Mechanical Design*, Vol. 125, No. 3, pp. 582–592, 2003.
11. Guo, W.Z., He, K., Yeung, K. and Du, R., "A new type of controllable mechanical press: Motion control and experiment validation", *Transaction of the ASME, Journal of Mechanical Design*, 2005, Vol. 127, No. 4, pp. 731–742, 2005.
12. Li, C.H. and Tso, P.L., "Experiment study on a hybrid-driven servo press using iterative learning control", *International Journal of Machine Tools & Manufacture*, Vol. 48, No. 2, pp. 209–219, 2008.
13. Soong, R.C., "An adjustable six-bar mechanism with variable input speed for mechanical forming presses", *Transactions of the Canadian Society for Mechanical Engineering*, Vol. 32, Nos. 3–4, pp. 453–466, 2008.
14. Li, H. and Zhang, Y., "Seven-bar mechanical press with hybrid-driven mechanism for deep drawing; Part 1: Kinematic analysis and optimum design", *Journal of Mechanical Science and Technology*, Vol. 24, No. 11, pp. 2153–2160, 2010.
15. Soong, R.C., "On the design of new programmable exact path generators", *Transactions of the Canadian Society for Mechanical Engineering*, Vol. 37, No. 3, pp. 685–692, 2013.