Synthesis of a Seven-Bar Slider Mechanism with Variable Topology for Motion between Two Dead-center Positions

Umesh M.Daivagna, *Member, IAENG*, Shrinivas S.Balli

Abstract—**The paper presents an analytical method to synthesize a seven-bar slider mechanism with variable topology for motion between two dead-center positions. Synthesis is carried out in two phases for motion generation between two dead-center positions. The tasks like path generation with prescribed timing and function generation are also dealt with. A dyadic complex number method is used. The complexity nature of synthesis of multi-degree freedom mechanisms made simpler through variable topology operating in two phases. The general attractions of the method are simplicity, ease of operation, easy to understand, codable for programming etc.**

Index Terms— **seven-bar slider, variable topology; dead-center positions, press working, complex numbers.**

I. Introduction

A seven-bar slider has two degrees of freedom. Various methods are proposed to synthesize it. A seven-bar slider with variable topology operates in two phases. In each phase, a link adjacent to the permanently fixed link of seven-bar slider is fixed temporarily and the resulting portion of the mechanism acts like a six-bar slider with single degree of freedom [1]. Metal forming is one of the oldest production processes and yet, it is one the most commonly used manufacturing technologies even today. In order to achieve the desirable punch motion, today many mechanical presses use multiple links. The metal forming operations like shearing, bending and deep drawing require different variable motions of the punch, like shearing requires very short stroke of the ram and deep drawing requires a slow and long stroke of the punch
[2, 3].The variable stroke lengths could be achieved by adjusting the link lengths as in case of adjustable mechanisms [4]. Here in this paper this is achieved through variable topology for seven-bar slider mechanism.

To begin with an overview of the available literature on variable topology is presented to form the basis of the present work. Rose [5], Ting and Tsai [6] and Ting [7] made indirect reference of five-bar variable topology mechanisms. Rawat [8] established a synthesis technique for a five-bar variable topology mechanism operating in two phases. Joshi et al. [9] and Joshi [10] used the dyad synthesis of a five-bar variable topology mechanism for circuit breaker applications. Balli and Chand dealt with motion between extreme positions [11], defects and solution rectification [12] of a five-bar variable topology mechanism. In the recent developments of mechanical presses, W.Z.Guo [2] et al. dealt with the design of mechanical press consisting of seven-bar slider mechanism of two degrees of freedom. Cai-Fang Meng et al [13] proposed the optimal design and control of a novel press with an extra motor. H. Zhou, Kwun-Lon Ting [2] dealt with adjustable slider-crank linkages for multiple path generation, T.S.Mruthunjaya [14] dealt with graphical synthesis of seven-bar mechanism. Daivagna and Balli [15] dealt with synthesis of an off-set five-bar slider mechanism with variable topology.

Many works on seven-bar linkages with variable topology mainly target on revolute joint type. Though there are works which deal with the five-bar slider crank linkages, they are not commonly found in industrial because of their limitations and difficulty in synthesizing [16].

In the methods presented above for variable topology mechanisms of seven-bar , off-set five-bar slider , the arbitrarily prescribed or chosen values lead to an infinite number of solutions to a given problem which result in a large domain of solution space. The solution obtained may be infeasible and one has to reiterate the solution steps till he/she gets a practically feasible mechanism, which functions satisfactorily. The criterion of motion of mechanism between its dead-center positions may be used to reduce the solution space between dead centers.

Since presses play a vital role in industry, further improvements in its synthesis adds a valuable contribution. Therefore, the objective of the present problem undertaken is to develop a non-iterative analytical method of solution to determine the links of a seven-bar slider mechanism with variable topology for motion between two dead-center positions of the mechanism. The stroke obtained in Phase-I is shorter than Phase-II. One can use Phase-I of the mechanism for the press which requires a shorter stroke and Phase-II of the mechanism may be used for the press which requires a longer stroke. Thus, a single seven-bar slider mechanism after synthesizing through variable topology method operates explicitly in Phase-I and Phase-II giving away two presses of different strokes which may be used for shearing and deep drawing operations .

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II. Seven-Bar Slider Mechanism With Variable Topology

Any mechanism with five or more links and with two or more degrees of freedom could be made to act as variable topology mechanism operating in two or more phases [10, 11]. The planar seven-bar slider mechanism is shown in Fig.1. The operations of the mechanism in Phase-I and Phase-II shown in Figs.2 and 3 respectively are discussed in the following paragraphs.

2.1 Phase-I

In Phase-I, the link O_cC is temporarily fixed and the resulting mechanism is a six-bar slider mechanism of single degree of freedom. It is a combination of five-bar slider and four-bar mechanism in series. O_aA_1 is the input link. B is the possible path tracer point. Suffix 1 and 2 of alphabets in Fig. 2 represent the two finitely separated positions of the six-bar slider portion of the seven-bar slider variable topology mechanism in Phase-I. C is a temporarily fixed pivot. O_a and O_c are the permanently fixed pivots.

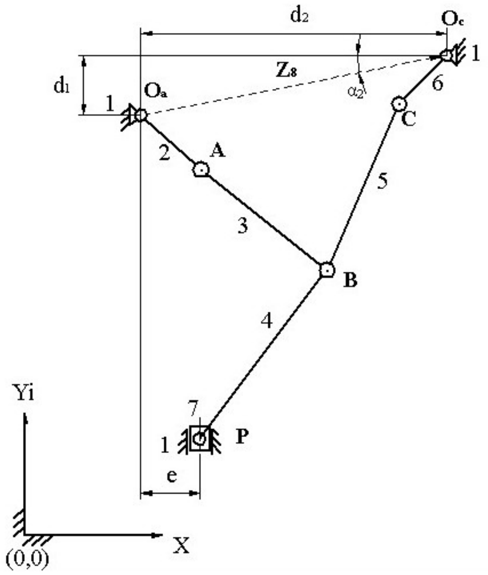

Fig. 1. A planar seven-bar slider mechanism

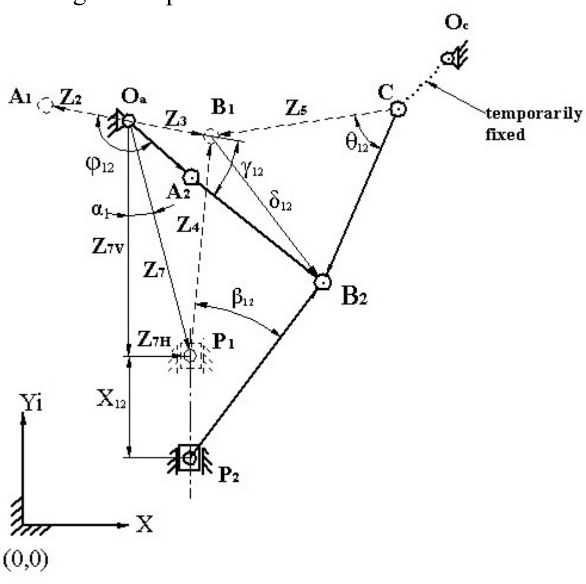

Fig. 2. A planar seven-bar slider mechanism with variable topology at its two dead-center positions, in Phase-I

2.2. Phase-II

Once the above six-bar slider portion of seven-bar slider mechanism with variable topology reaches the position 2 , the link O_cC is released to move and the link O_aA is fixed temporarily, thus switching on to the Phase-II. Again the resulting mechanism is six-bar slider of single degree of

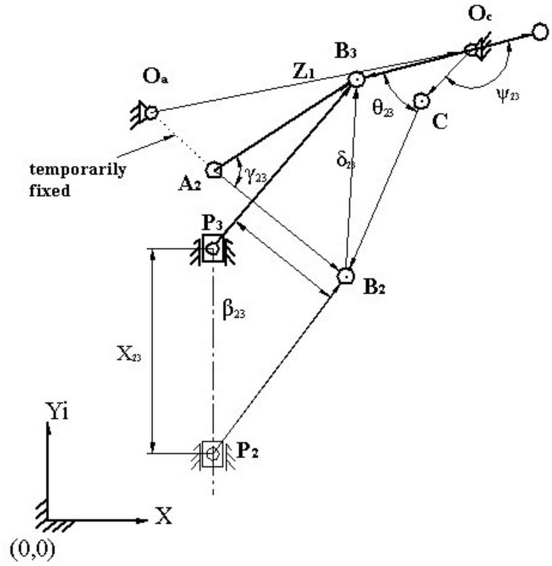

Fig. 2. A planar seven-bar slider mechanism with variable topology at its two dead-center positions, in Phase-II

freedom. Here link O_cC is input link, B is the tracer point. Suffix 2 and 3 of alphabets in Fig.3 represent the two finitely separated positions of the six-bar slider portion of the seven-bar slider variable topology mechanism in Phase-II. Also, it is to be noted that C is no more a fixed pivot where as A_2 is a temporarily fixed pivot. O_c and O_a are the permanently fixed pivots.

III. Synthesis

3.1 Solution steps

The solution to the problem consists of the following steps:

(i) Identification of the links to be fixed temporarily in each phase so that in both the phases one can get six-bar slider portion of seven-bar slider variable topology mechanism.

(ii) Recognization of the type of mechanism in each phase.

(iii) Writing of the standard dyad equations for the motion between position 1 and position 2 of Phase-I and also between position 2 and position 3 of Phase-II.

(iv) Identification of the values to be prescribed, values to be chosen freely and the unknowns based on the task to be performed.

(v) Solving of the equations of motion in each phase for the link lengths.

(vi) Retaining of link parameters determined in Phase-I while solving other link lengths in Phase-II.

(vii) Finding of the total number of solutions that are possible in all phases by the method.

When it is required to synthesize a planar seven-bar slider mechanism (shown in Fig.1) with variable topology, one can have three options as follows:

(i) One end link is fixed temporarily,

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(ii) Other end link is fixed temporarily,

(iii) Middle link, the slider is fixed temporarily.

The options (i) and (ii) are considered for the present paper. It is assumed that the mechanism moves from dead center position 1 to the dead center position 2 in Phase-I and from the dead center position 2 to the dead center position 3 in Phase-II. In the present case, as soon as the mechanism moves from one dead-center position to the other, it stops and then switches on to the Phase-II. So there is no question of overcoming the dead lock and hence, no auxiliary drive is needed. Moreover, the dead lock positions can overcome by inertia forces of the cranks.

Table I

Conventions to be followed to denote the linkages and the angles in Phase-I and in Phase-II

Link Vectors and angles	Phase-I Position 1 to 2	Phase-II Position 2 to 3
$O_aA_1 = \mathbf{Z}_2$, φ	φ_{12}	Temporarily fixed
$A_1B_1 = \mathbf{Z_3}$,γ	γ_{12}	γ_{23}
$B_1P_1 = \mathbf{Z}_4$,β	β_{12}	β_{23}
$C_1B_1 = \mathbf{Z_5}$, θ	θ_{12}	θ_{23}
$O_cC = \mathbf{Z_6}$, ψ	Temporarily fixed	ψ_{23}
$O_aC = \mathbf{Z_1}$	From O_a to C	-----
$O_aP = \mathbf{Z_7}$	From O_a to P_1	-----
$\mathbf{X_{12}}$, $\mathbf{X_{23}}$	Slider displacement	slider displacement
$\rho_{12} = \mathbf{Z_{7V}} + \mathbf{X_{12}} / \mathbf{Z_{7V}}$	ρ_{12} is Stretch ratio	-----
$\mathbf{Z_{7H}}$ =e	Eccentricity between O_a and slider path	-----
$O_aO_c = \mathbf{Z_8}$	From O_a to O_c	-----
$\mathbf{Z_{8V}} = d_1$	Vertical offset for O_aO_c	-----
$\mathbf{Z_{8H}} = d_2$	Horizontal offset for O_aO_c	-----
Displacement vector	$B_1B_2 = \delta_{12}$	$B_2B_3 = \delta_{23}$
Number of solutions	∞^6	∞^1
Total number of solutions	∞^7	
Sign convention	CCW motion is +ve Linear displacement upward is +ve	CW motion is –ve , Downward is -ve

The conventions to be followed in Phase-I and Phase-II are given in Table 1. The input motion in Phase-I is φ_{12} , the displacement vector B_1B_2 is given by δ_{12} .

Writing the dyad equations [1, 17] for Phase-I (refer Fig.2),

$$\mathbf{Z}_2 (e^{i\varphi_{12}} - 1) + \mathbf{Z_3} (e^{i\gamma_{12}} - 1) = \delta_{12} \tag{1}$$

$$\mathbf{Z_{7H}} (\rho_{12} - 1) + \mathbf{Z}_4 (e^{i\beta_{12}} - 1) = \delta_{12} \tag{2}$$

$$\mathbf{X_{12}} + \mathbf{Z}_4 (e^{i\beta_{12}} - 1) = \delta_{12} \tag{3}$$

$$\mathbf{Z_5} (e^{i\theta_{12}} - 1) = \delta_{12} \tag{4}$$

3.2 Motion generation

In motion generation mechanisms, the body to be guided usually is a part a floating link. Hence, the location of tracer point on the coupler and the coupler orientation are the part of design specifications as the entire motion of the coupler link is to take place. It requires that an entire body be guided through a prescribed motion order.

3.2.1 Phase-I synthesis

In the standard dyad Eqs.(1)-(4), in motion generation, the coupler point motions (γ_{12}, β_{12}) and the displacement vector δ_{12} are prescribed. φ_{12} , $\mathbf{X_{12}}$, θ_{12} and $\mathbf{Z}_2$ are the free choices. Hence, there will be ∞^6 numbers of solutions. Then the unknowns $\mathbf{Z_3}$, $\mathbf{Z}_4$, $\mathbf{Z_5}$, $\mathbf{Z_7}$ and $\mathbf{Z_1}$ are determined as follows;

$$\mathbf{Z_3} = \frac{\delta_{12} - \mathbf{Z_2}(e^{i\varphi_{12}} - 1)}{(e^{i\gamma_{12}} - 1)} \tag{5}$$

$$\mathbf{Z}_4 = \frac{\delta_{12} - \mathbf{X_{12}}}{(e^{i\beta_{12}} - 1)} \tag{6}$$

$$\mathbf{Z_5} = \frac{\delta_{12}}{(e^{i\theta_{12}} - 1)} \tag{7}$$

From loop closure equation,

$$\mathbf{Z_7} = \mathbf{Z}_2 + \mathbf{Z_3} - \mathbf{Z}_4 \tag{8}$$

$$\mathbf{Z_1} = \mathbf{Z}_2 + \mathbf{Z_3} - \mathbf{Z_5} \tag{9}$$

Also, $\mathbf{Z_7} = \mathbf{Z_{7V}} + \mathbf{Z_{7H}}$ (10)

Off-set = e = $\mathbf{Z_{7H}} = - \mathbf{Z_7} \text{ Sin } \alpha_1 \; e^{i(90-\alpha_1)}$ (11)

Where α_1 is the angle made by $\mathbf{Z_7}$ with the vertical line passing through O_a in CW.

3.2.2 Phase-II synthesis

Input motion in Phase-II is ψ_{23} the displacement vector B_1B_2 is given by δ_{23} .

Writing the dyad equations for Phase-II (refer Fig. 3)

$$\mathbf{Z_6} (e^{i\psi_{23}} - 1) + \mathbf{Z_5} \, e^{i\theta_{12}} (e^{i\theta_{23}} - 1) = \delta_{23} \tag{12}$$

$$\mathbf{Z_3} \; e^{i\gamma_{12}} \; (e^{i\gamma_{23}} - 1) = \delta_{23} \tag{13}$$

$$\mathbf{X_{23}} + \mathbf{Z}_4 \, e^{i\beta_{12}} (e^{i\beta_{23}} - 1) = \delta_{23} \tag{14}$$

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Here δ_{23} and θ_{23} are prescribed, γ_{23} is a free choice. Therefore, there will be ∞^1 number of solutions. Hence the total number of solutions from Phase-I and Phase-II are ∞^7. The link lengths determined in Phase-I are retained in Phase-II Then, the unknowns $\mathbf{Z_6}$, $\mathbf{Z_8}$, vertical off-set d_1 and horizontal off-set d_2 (refer Fig.3) are determined as follows;

$$\mathbf{Z_6} = \frac{\delta_{23} - \mathbf{Z_5} e^{i\theta_{12}} (e^{i\theta_{23}} - 1)}{(e^{i\psi_{23}} - 1)} \tag{15}$$

From loop closure equation,

$$\mathbf{Z_8} = \mathbf{Z}_2\, e^{i\varphi_{12}} + \mathbf{Z_3}\, e^{i\gamma_{12}} \quad \mathbf{Z_5}\, e^{i\theta_{12}} - \mathbf{Z_6} \tag{16}$$

Now, α_2 is the angle made by $\mathbf{Z_8}$ with the horizontal line passing through O_c in CW (refer Fig.3)

$$\text{Vertical off-set} = d_1 = \mathbf{Z_{8V}} = \mathbf{Z_8} \operatorname{Sin} \alpha_2\, e^{i\alpha_2} \tag{17}$$

$$\text{Horizontal off-set} = d_2 = \mathbf{Z_{8H}} = \mathbf{Z_8} \operatorname{Cos} \alpha_2\, e^{-i(90-\alpha_{21})} \tag{18}$$

3.3 Path generation with prescribed timing

In path generation a point on a floating link is to trace a path defined with respect to the fixed frame. If the path points are to be correlated with either time or input link positions, the task is called as path generation with prescribed timings. For this purpose, location of a tracer point on the coupler and the position of the input link are the part of the design specifications. The position of the link must correspond to each position of the tracer point on the coupler. The path of tracer point i.e. motion of coupler point and rotation of one crank are to be prescribed. The values to be prescribed and to be chosen freely in case of motion generation problem are to be interchanged for the path generation with prescribed timing [1, 17].

3.3.1 Phase-I synthesis

The input crank motion $\varphi_{12,}$ linear displacement vector $\mathbf{X_{12}}$, θ_{12} and δ_{12} are prescribed. γ_{12} , β_{12} and $\mathbf{Z_2}$ are the free choices. Hence, there will be ∞^4 number of solutions .Then the unknowns $\mathbf{Z_3}, \mathbf{Z_4}, \mathbf{Z_5}, \mathbf{Z_7}, \mathbf{Z_1}$ and e are determined using the Eqs. 5-11 respectively.

3.3.2 Phase-II synthesis

Prescribed parameters are δ_{23} and ψ_{23} and θ_{23} is a free choice. Therefore, there will be ∞ number of solutions. $\mathbf{Z_6}$, $\mathbf{Z_8}$, d_1 and d_2 are determined using Eqs. 15-18 respectively.

3.4 Function generation

In function generation mechanism, relative motion or forces between links connected to ground is taken into account. It is required to coordinate the rotation or sliding motion of input and output links for two specified design positions [1, 17, and 18].

3.4.1 Phase-I synthesis

In function generation problem, the output and input motion are φ_{12}, $\mathbf{X_{12}}$, θ_{12} and $\mathbf{Z_5}$ are prescribed. γ_{12} , β_{12} and $\mathbf{Z_2}$ are free choices.Therefore, there will be ∞^4 numberofsolutions.Then unknowns $\mathbf{Z_3}, \mathbf{Z_4}, \mathbf{Z_7}, \mathbf{Z_1}$ and e are determined as follows;

$$\mathbf{Z}_2 (e^{i\varphi_{12}} - 1) + \mathbf{Z_3} (e^{i\gamma_{12}} - 1) = \mathbf{Z_5} (e^{i\theta_{12}} - 1) \tag{19}$$

$$\mathbf{X_{12}} + \mathbf{Z}_4 (e^{i\beta_{12}} - 1) = \mathbf{Z_5} (e^{i\theta_{12}} - 1) \tag{20}$$

$$\text{Let } \mathbf{Z_5} (e^{i\theta_{12}} - 1) = \delta_{12} \tag{21}$$

Where δ_{12} is the displacement of the vector B_1B_2.

Reducing the Eqs.19 and 20 to the forms of standard dyadic equations [1, 11, 17, and 18] as follows;

$$\mathbf{Z}_2 (e^{i\varphi_{12}} - 1) + \mathbf{Z_3} (e^{i\gamma_{12}} - 1) = \delta_{12} \tag{22}$$

$$\mathbf{X_{12}} + \mathbf{Z}_4 (e^{i\beta_{12}} - 1) = \delta_{12} \tag{23}$$

$$\mathbf{Z_3} = \frac{\delta_{12} - \mathbf{Z_2} (e^{i\varphi_{12}} - 1)}{(e^{i\gamma_{12}} - 1)} \tag{24}$$

$$\mathbf{Z}_4 = \frac{\delta_{12} - \mathbf{X_{12}}}{(e^{i\beta_{12}} - 1)} \tag{25}$$

$\mathbf{Z_7}, \mathbf{Z_1}$ and e are determined using Eqs. 8-11respectively.

3.4.2 Phase-II synthesis

Writing the loop closure equation for the Phase-II (refer Fig.3),

$$\mathbf{Z_6} (e^{i\psi_{23}} - 1) + \mathbf{Z_5}\, e^{i\theta_{12}} (e^{i\theta_{23}} - 1) = \mathbf{Z_3}\; e^{i\gamma_{12}}\; (e^{i\gamma_{23}} - 1) \tag{26}$$

$$\mathbf{X_{23}} + \mathbf{Z}_4\, e^{i\beta_{12}} (e^{i\beta_{23}} - 1) = \mathbf{Z_3}\; e^{i\gamma_{12}}\; (e^{i\gamma_{23}} - 1) \tag{27}$$

$$\text{Let } \mathbf{Z_3}\; e^{i\gamma_{12}}\; (e^{i\gamma_{23}} - 1) = \delta_{23} \tag{28}$$

Reducing the Eqs. 26 and 27 to the forms of standard dyadic equations [1, 17] as follows;

$$\mathbf{Z_6} (e^{i\psi_{23}} - 1) + \mathbf{Z_5}\, e^{i\theta_{12}} (e^{i\theta_{23}} - 1) = \delta_{23} \tag{29}$$

$$\mathbf{X_{23}} + \mathbf{Z}_4\, e^{i\beta_{12}} (e^{i\beta_{23}} - 1) = \delta_{23} \tag{30}$$

Here ψ_{23}, X_{23} and β_{23} are prescribed and θ_{23} is the free choice. Therefore, there will be ∞ number of solutions. $\mathbf{Z_6}, \mathbf{Z_8}$, d_1 and d_2 are determined as follows;

When δ_{23} (or γ_{23}) and ψ_{23} are prescribed.

$$\mathbf{Z_6} = \frac{\mathbf{X_{23}} + \mathbf{Z_4} e^{i\beta_{12}} (e^{i\beta_{23}} - 1) - \mathbf{Z_5} e^{i\theta_{12}} (e^{i\theta_{23}} - 1)}{(e^{i\psi_{23}} - 1)} \tag{31}$$

$\mathbf{Z_8}$, d_1 and d_2 are determined using Eqs. 16-18 respectively.

IV. Solution Space

The method gives an infinite number of solutions depending upon the number of free choices made. In order to obtain practically useful mechanisms, it is necessary to reduce the solution space by calculating the free choices in terms of known parameters. [1, 17].

V. Advantages of the Method

The dyad technique by Sander and Erdman permits handling any type of bar-slider mechanism and is extensively used for the synthesis of single degree of freedom mechanisms. Here it has been applied to variable topology mechanisms, which in this case are two degrees of freedom systems. The method reduces the job of synthesizing seven-bar slider mechanism of two degrees of freedom to design a six-bar slider mechanism with one degree of freedom in two phases. The synthesis of a six-bar slider mechanism is simpler. Thus the method is simpler compared with other methods of synthesis of seven-bar slider mechanism. Following are the some of the advantages of the method.

- Simplicity, ease of application and generality.
- Increased accuracy over graphical methods.

VI. Limitations of the Method

- The proposed method is applicable to complex number approach.

- The synthesized mechanism by the method may suffer from defects like circuit and branch which can be rectified separately.
- The solution does not permit good initial free choices for all possible solutions.

VII. Application of the Method

The synthesized seven-bar slider mechanism with variable topology can be applied to mechanical press operations. The steps involving in these operations are as follows;

- Let the input motor for the mechanism be link 2 in Phase-I and link 6 in Phase-II.
- For the shearing operation (Phase-I), let the input parameter link 6 be temporarily fixed or locked.
- The punch and die for the operation may be suitably arranged to perform the shearing.
- Switch on the motor, one can operate the shearing operation.
- After the completion of the shearing, release the link 6 and temporarily fix or lock link 2.
- The punch and die for the drawing operation may be suitably arranged.
- Switch on the second motor of link 6 and one can carryout the drawing operation.

Thus the same press can be used for multiple operations, thus it is economical.

VIII. Conclusion

The proposed method is for the synthesis of seven-bar slider mechanism with variable topology for the motion generation between two dead-center positions. In the present work, order is not significant as the numbers of design positions are two. The synthesized mechanism is free from Grashof's because of rotary inputs of the mechanism in both the phases. There may be circuit and branch defects [12]. The proposed method reduces the synthesis of seven-bar slider mechanism of two degrees of freedom to the synthesis of a six-bar slider mechanism but in two phases of operations. The application and the advantages of the method to shearing in Phase-I and drawing in Phase-II is discussed. The method proposed is simple, easy to understand. The authors are more concerned with developing the variable topology mechanisms for the industrial purpose to save cost and energy. The solution rectification of the proposed mechanism is to be undertaken in the future work.

Example

It is required to synthesize a seven-bar slider mechanism with variable topology for the motion between two dead-center positions, used for press working operations in two phases. Following are the tracer point displacement specifications;

Phase-I: from point (107.0600, 149.0600) to the point (142.2800, 103.0600)

Prescribed parameters are $\gamma_{12} = -27.94^0$ and $\beta_{12} = -31.58^0$

Phase-II: from point (142.2800, 103.0600) to the point (154.3900, 139.6400)

Prescribed parameters are $\delta_{23} = (12.11 +36.58i)$, $\theta_{23} = -5.66^0$ CW

Solution: (a) Motion generation

Phase-I: Given that: displacement $=\delta_{12} = (35.22 -46.0i)$, $\gamma_{12} = -27.94^0$ and $\beta_{12} = -31.58^0$ (Prescribed parameters)

Let $\mathbf{Z}_2 = (-26.14 + 4.92i)$, $\mathbf{X_{12}} = (0\text{-}33.03i)$, $\theta_{12} = +58.22^0$ and $\varphi_{12} = +144.53^0$ (Free choices)

From Eq.5,

$\mathbf{Z_3} = (52.0775\text{-}9.7811i) = 52.9775 \angle 169.3606^0$

From Eq.6,

$\mathbf{Z}_4 = (5.3228+68.7590i) = 68.9647 \angle 85.5734^0$

FromEq.7,

$\mathbf{Z_5} = (-58.9157–8.6260i) = 59.5439 \angle 188.3296^0$

FromEq.5,

$\mathbf{Z_7} = (20.6039–73.6300i) = 76.4585 \angle 288.6332^0$

From Eq.9,

$\mathbf{Z_1} = (84.7824 + 3.7649i) = 84.8660 \angle 2.5427^0$

From Eq.11,

Off-set = e = $(20.6038 +0i) = 20.6038 \angle 0^0$

Phase-II: Given that: displacement, $\delta_{23}=(12.11+ 36.5800i)$ and $\theta_{23} = -5.66^0$ CW

Let $\psi_{23} = +174.34^0$ CCW (free choice)

From Eq.15,

$\mathbf{Z_6} = (-9.5310\text{-}16.5586i) = 19.1057 \angle 240.0755^0$

From Eq.16,

$\mathbf{Z_8} = (96.5371+20.3235i) = 96.5371 \angle 12.1531^0$

From Eq.17,

$\mathbf{Z_{8V}}$ = Vertical offset, $d_1 = (0+20.3300i) = 20.3300 \angle 90^0$

From Eq.18,

$\mathbf{Z_{8H}}$ =Horizontal off-set, $d_2 = (94.3735+0i) = 97.3735 \angle 0^0$

(b) Path generation with prescribed timing

Phase-I: Given that: displacement $=\delta_{12} = (35.22 -46.0i)$, $\varphi_{12} = +144.53^0$, $\mathbf{X_{12}} = (0\text{-}33.03i)$ and $\theta_{12} = +58.22^0$

Let $\mathbf{Z}_2 = (-26.14 + 4.92i)$, $\gamma_{12} = -27.94^0$ and $\beta_{12} = -31.58^0$ (Free choices)

From Eq.5,

$\mathbf{Z_3} = (52.0775\text{-}9.7811i) = 52.9775 \angle 169.3606^0$

From Eq.6,

$\mathbf{Z}_4 = (5.3228+68.7590i) = 68.9647 \angle 85.5734^0$

FromEq.7,

$\mathbf{Z_5} = (-58.9157\text{-}8.6260i) = 59.5439 \angle 188.3296^0$

FromEq.5,

$\mathbf{Z_7} = (20.6039–73.6300i) = 76.4585 \angle 288.6332^0$

From Eq.9,

$\mathbf{Z_1} = (84.7824 + 3.7649i) = 84.8660 \angle 2.5427^0$

From Eq.11,

Off-set = e = $\mathbf{Z_{7H}} = (20.6038 +0i) = 20.6038 \angle 0^0$

Phase-II: Given that:

Displacement, $\delta_{23}= (12.11 + 36.5800i)$ and $\psi_{23} = +174.34^0$

Let $\theta_{23} = -5.66^0$ CW (free choice)

FromEq.15,

$\mathbf{Z_6} = (-9.5310\text{-}16.5586i) = 19.1057 \angle 240.0755^0$

From Eq.16,

$\mathbf{Z_8} = (96.5371 + 20.3235i) = 96.5371 \angle 12.1531^0$

From Eq.17,

$\mathbf{Z_{8V}} = d_1$ =Vertical offset Off-set

$= (0+20.3300i) = 20.3300 \angle 90^0$

From Eq.18,

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$\mathbf{Z_{8H}}$ =d_2 =Horizontal off-set
= (94.3735+0i) =97.3735 $\angle$ 0^0

(b) Function generation

Phase-I: Given that: φ_{12} = +144.53^0 , $\mathbf{X_{12}}$ = (0-33.03i) and θ_{12} = +58.22^0 and $\mathbf{Z_5}$ = (-58.9157 – 8.6260i)

From Eq. 21, displacement =δ_{12} = (35.22 -46.0i),

Let $\mathbf{Z}_2$ = (-26.14 + 4.92i), γ_{12} = -27.94^0 and β_{12} = -31.58^0 (Free choices)

From Eq.24,
$\mathbf{Z_3}$ = (52.0775-9.7811i) = 52.9775 $\angle$ 169.3606^0

From Eq.25,
$\mathbf{Z}_4$ = (5.3168 + 68.7562i) = 68.9615 $\angle$ 85.5782^0

From Eq.5,
$\mathbf{Z_7}$ = (20.6099 – 73.6273i) = 76.4575 $\angle$ 285.6381^0

From Eq.9,
$\mathbf{Z_1}$ = (84.7824 + 3.7649i) = 84.8660 $\angle$ 2.5427^0

From Eq.11,
Off-set = e = $\mathbf{Z_{7H}}$ = (20.6100 +0i) = 20.6100 $\angle$ 0^0

Phase-II:

Given that: ψ_{23}=+174.34^{0}CCW, $\mathbf{X_{23}}$ =(0+47.6300i), β_{23} = -13.7600^0, $\mathbf{Z_3}$ = (52.0775-9.7811i) and γ_{23} = 42.78^0 CCW .θ_{23} = -5.66^0 CW (free choice)

From Eq.28, δ_{23} = (11.4207 + 36.9174i)

From Eq.31,
$\mathbf{Z_6}$ = (-9.1954 – 16.7443i) = 19.1031 $\angle$ 241.2259^0

From Eq.16,
$\mathbf{Z_8}$ = (94.0378 + 20.4992i) = 96.2462 $\angle$ 12.2975^0

From Eq.17,
$\mathbf{Z_{8V}}$ =d_1=Vertical offset= (0 + 20.3300i) = 20.5004 $\angle$ 90^0

From Eq.18,
$\mathbf{Z_{8H}}$ =d_2=Horizontal off-set=(94.0378+0i)= 94.0378 $\angle$ 0^0

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