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“Two FSP Synthesis of Seven Bar Slider Mechanism Using Variable Topology”

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ABSTRACT

Mechanisms are of the prime consideration while running the machines. Therefore the synthesis of mechanisms will be the key factor in the mechanical design. Synthesis becomes comparatively easy when the mechanism is of single degrees of freedom (DOF) and will be difficult as the number of DOF increases. There are many methods used for the synthesis of mechanisms with more links and with two or higher degrees-of-freedom that are complicated and prolonged. These complicated/ higher DOF mechanisms can be easily synthesized by converting them into Variable Topology Mechanism (VTM) which operates in multi phases. The present proposed work has an application of VTM in the Automatic Fiber Replacement Mechanism and is operating in two phases and for extreme positions. This reduces the solution space for function generation, path generation and rigid body guidance/ motion generation tasks with no iterations.

Keywords: Complex number, Dyads, Dimensional Synthesis, VTM

1. INTRODUCTION

After the industrial revolution and in the advanced technological modern era, machines play an important role in producing the goods in large quantities and in a faster way. These machines operate based on the mechanism they are made-up of. The synthesis of mechanisms becomes easy when they are operating with lower pairs and with single degree of freedom system. With mechanism having only lower pairs and lower DOF system is not possible to perform the multiple tasks. This tends to use higher pairs and/or a higher DOF system. As the number of DOF increases, synthesis process becomes difficult. Synthesis of the mechanism involves the determining of link lengths and their orientations to perform the required task. The tasks can be motion generation, path generation and function generation based upon the requirement. There are many methods used for the synthesis of mechanisms with higher number of links and with higher degrees-of-freedom which are complex in nature leading to time-consuming. But, these mechanisms can be converted into variable topology mechanism which operates in multiple phases based on the number of degrees of freedom of original mechanism.

1.1. Variable Topology Method

A variable topology mechanism operates in multiple phases (two or more)^[1]. To reduce the degrees of freedom (DOF), a link is fixed temporarily. This link is next to the permanently fixed link. This results in a single DOF mechanism^[2]. In this phase all link lengths are determined by complex number approach. In next phase, the previously temporarily fixed link is made free to have motion and another link is fixed temporarily. This link is also preferably is next to the permanently fixed one. This procedure is followed in each phase so that the mechanism reduces to have single DOF in each phase and can be easily synthesized. Until the 1960s, researchers used graphical techniques to synthesize the higher DOF mechanism. Rawat^[3] exhibits synthesizing process of 5 bar mechanism with Variable Topology Method. Joshi and Amaranth^[4] developed the VTM by involving Loop Closure equations in it. Balli and Chand investigate a technique to synthesize the planar 5-bar mechanism of VTM type for movement between positions^[1]. which is free from order defect^[5], also with the transmission angle control^[6], they have dealt with the 7-link VTM for two dead-center positions^[7].



These papers enlighten a mathematical method to find out the position and length of the links of mechanism and possible ways to reduce the solution space with lesser iterations.

Daivagna and Balli investigated the synthesis procedure for seven-bar slider mechanism with VTM for motion between dead-center positions^{[8][9]}; triad and dyad synthesis of 7 bar mechanism with variable topology for the task like function generation^{[10][11]}; In the papers, the authors developed a technique to synthesize a 5-bar slider with VTM. Dyadic complex number procedure is used to write motion equations and increase the accuracy over graphical process and also they determined the FSP Synthesis of an off-set 5 bar-slider with variable topology^{[12][13]}.

The reviews of papers indicate the scope for research to convert the 7-bar slider mechanism into VTM for the applications such as Automatic Fiber Placement (AFP)^{[14][15]}. Hence in this paper, the author focused on the synthesis of 7 bar slider mechanism using VTM which operates between two extreme positions. With complex number and dyadic approaches, analytical equations are written and solved.

2. SEVEN BAR SLIDER MECHANISM

The original 7 bar slider mechanism with 2 degrees of freedom is shown in Figure 1.0. In which O_aO_b and O_bO_c are permanent links and slider D slides along with the link O_bB . This mechanism is of 2 DOF; hence the proposed VTM is operating in two Phases.

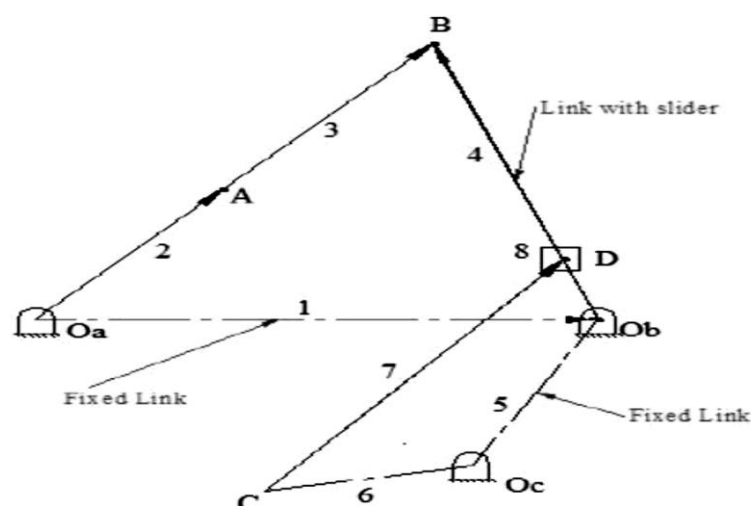


Fig.1.0: Bar slider mechanism

2.1. Variable Topology Mechanism Phases

The process of synthesis by VTM is having following steps:

- The number of phases is decided based on the number of DOF of a mechanism.
- To reduce the higher DOF to single DOF, the link going to be temporarily fixed is decided to be the link is next to the fixed link.
- Recognition of the tasks to be performed by a mechanism in each phase.
- For both the phases, standard dyad equations are written for the motion between extreme positions.
- Based on the equations of motion and tasks to be performed, the prescribed, free choice and unknown values are to be identified.
- Finding the total solution space (number of solutions) of the mechanisms in all phases.
- By solving the equation of motion, link lengths are determined in every phase.
- Solving the equations of Phase II by retaining the Phase I parameters which are already determined.

2.2. Mechanism operating in Phase-I

In Phase – I synthesis, link O_cC which is the link next to fixed link O_bO_c is temporarily fixed and input is given to link O_aA . After fixing the link; the mechanism will be converted into 6 bar slider mechanism with single DOF as shown in Figure 1.1. O_cC when temporarily fixed, O_bO_c and O_cC become one rigid link leads to formation of vector Z_{10} . In this phase when the input motion is given to link O_aA , the mechanism will move from position 1 to 2.

Now, O_aA_1 is the input link and A_1B_1 is the coupler. The angular motion of the coupler link A_1B_1 to A_2B_2 is α_{12} . By definition, the angle between the coupler (A_1B_1) and follower link (O_bB_1) is known as the Transmission angle and is denoted by μ [16]. The slider D will slide from position D_1 to D_2 along link O_bB_1 . Because this link is having angular motion, the slider also experience both sliding and angular motion.

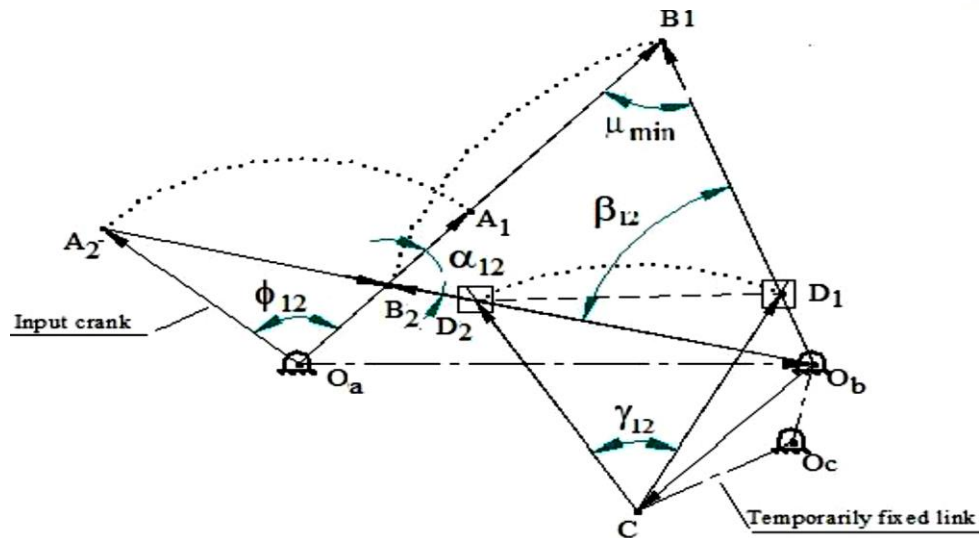


Fig.1.1:7 bar slider Variable Topology Mechanism in Phase – I

2.3.Mechanism operating in Phase-II

In phase – II, the previously short timely fixed link CO_c will be released and link O_aA is going to be fixed temporarily. The input motion is provided to link O_cC . Now, this mechanism will act as a slider mechanism as shown in Figure 1.2. When the input motion is given, the slider will move from D_2 to D_3 . Once the link O_aA_2 is fixed temporarily, the portion $O_aA_2B_2O_bO_a$ is resulted in 3 bar truss element. Hence there is no motion for links O_aA_2 , A_2B_2 and O_bB_2 . Also, the slider will have only a linear motion.

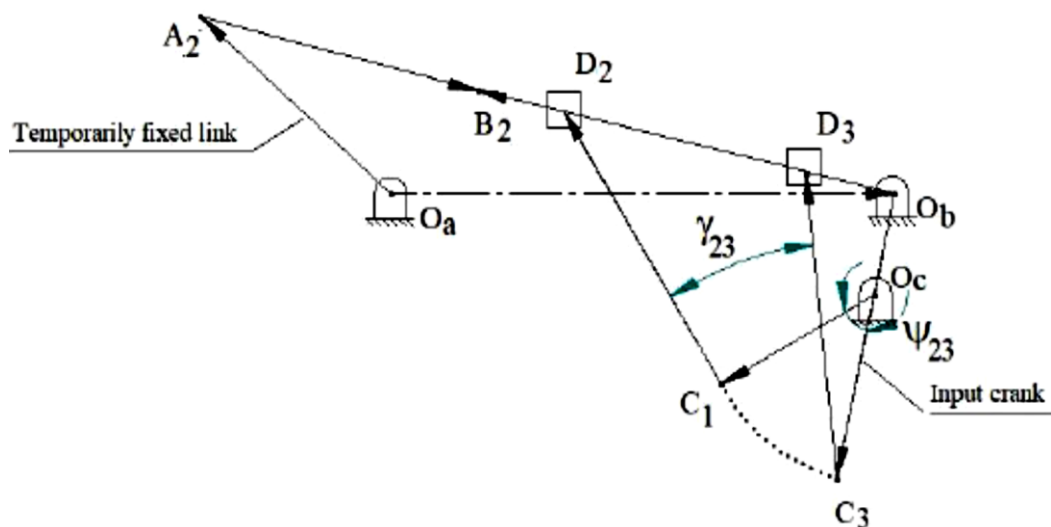


Fig.1.2: 7 bar slider Variable Topology Mechanism in Phase II

3. PROBLEM DESCRIPTION

In the present work, the two positions considered in Phase I are at the extreme positions. i.e., the input link and coupler are along one line at one extreme position and follower and coupler are inline at another extreme position. So, the transmission angle is at some value in one Phase I and reaches 180° in Phase II. When the transmission angle is 180° , the mechanism will be self-locked which is desirable for operating in phase II.

Table 1. Conventions used to indicate the linkages and the angles in both the phases

Link Vectors and angular motion	Phase – I	Phase – II
	From Position 1 to 2	From Position 2 to 3
$O_aO_b = Z_1$	Permanently fixed	Permanently fixed
$O_bO_c = Z_5$	Permanently fixed	Permanently fixed
$O_aA = Z_2, \phi$	Input Link, ϕ_{12}	Temporarily fixed
$A_1B_1 = Z_3, \alpha$	α_{12}	----
$O_bB_1 = Z_4, \beta$	β_{12}	----
$O_cC_1 = Z_6, \psi$	Temporarily fixed	Ψ_{23}
$C_1D_1 = Z_7, \gamma$	γ_{12}	γ_{23}
$O_bD_1 = Z_8, \beta$	β_{12}	----
$O_bD_2' = Z_9, \beta$	β_{12}	----
$O_bC = Z_{10}$		
X_{12}, X_{23}	Slider Displacement	Slider Displacement
$B_1B_2 = d'$	Displacement Vector	-----
Sign Convention	CCW motions are +ve, CW motions are –ve.	

4. SYNTHESIS OF MECHANISM

4.1.Motion Generation

In case of motion generation, the body to be guided is a part of a floating link. Here, positions of the path tracing point on the coupler as well as the direction of the coupler motion are the main concerns in mechanism design. It necessitates that whole body be guided in a prescribed motion order ^[17].

4.1.1.Phase – I Synthesis

The conventions followed in Phase – I are given in Table 1. The input motion in Phase –I is ϕ_{12} . The displacement vector B_1B_2 is given by d_{12} . Referring to Figure 1.1, the dyad equations for Phase – I are as follows:

$$Z_2 (e^{i\phi_{12}} - 1) + Z_3 (e^{i\alpha_{12}} - 1) = \delta_{12} \quad (1)$$

$$Z_4 (e^{i\beta_{12}} - 1) = \delta_{12} \quad (2)$$

$$Z_9 e^{i\beta_{12}} - Z_8 = X_{12} \quad (3)$$

$$Z_7 (e^{i\gamma_{12}} - 1) = X_{12} \quad (4)$$

Vector loop equations are

$$Z_1 = Z_2 + Z_3 - Z_4 \quad (5)$$

$$Z_{10} = Z_8 - Z_7 \quad (6)$$

In the standard dyad Eqns. (1) to (4), for motion generation problem, the coupler point motions (α_{12} , γ_{12}) and displacement vector d_{12} are specified. For 2 position synthesis and from dyad equations, the number of free choices is determined as the difference between the number of unknowns and the number of scalar equations. Here, in this case, the number of unknowns is 16, and the number of scalar equations is 8, hence the number of free choices is $16 - 8 = 8$. Hence, there will be eight free choices leading to the number of solutions as ∞^8 .

Let us consider the condition that the displacement vector d_{12} and input vector Z_2 are inline. Then by the vector algebra,

The angle of vector d_{12} = Angle of Vector Z_2

$$\text{i.e.} \quad \tan^{-1} \left(\frac{\delta_{12y}}{\delta_{12x}} \right) = \tan^{-1} \left(\frac{Z_{2y}}{Z_{2x}} \right) \quad (7)$$

Hence d_{12} is prescribed and one coordinate of Z_2 is assumed, remaining coordinate can be determined.

Similarly, vector Z_4 , Z_8 , and Z_9 are inline.



$$\text{So, } \tan^{-1} \left(\frac{Z_{4y}}{Z_{4x}} \right) = \tan^{-1} \left(\frac{Z_{8y}}{Z_{8x}} \right) \quad (8)$$

$$\tan^{-1} \left(\frac{Z_{4y}}{Z_{4x}} \right) = \tan^{-1} \left(\frac{Z_{9y}}{Z_{9x}} \right) \quad (9)$$

Since the orientation of Z_4 is found by the equation (2), if anyone coordinator of Z_8 and Z_9 vector is assumed, then remaining coordinate would find out by the above equations.

As per the description of the problem, position 1 & 2 are at extreme positions as shown in Figure 1.1. From Triangle $O_bB_1B_2$

$$O_bB_2B_1 = \alpha_{12}$$

The transmission angle is minimum at position 1. i.e., by the definition of transmission angle and by referring the Figure 1.0, transmission angle $O_bB_1B_2 = \mu_{\min}$. As O_bB_1 and O_bB_2 are equal, $O_bB_1B_2$ forms an isosceles triangle. So

$$O_bB_1B_2 = O_bB_2B_1 = \alpha_{12} = \mu_{\min}.$$

$$\beta_{12} = 180^\circ - 2 \mu_{\min}$$

Hence, from the above equations, the 4 parameters are prescribed and hence the solution space will reduce from ∞^8 to ∞^4 . Now Z_2 , ϕ_{12} , Z_8 , and Z_9 are free choices and Z_3 , Z_4 , X_{12} , Z_1 , Z_{10} , and Z_7 are to be found out by the equations (1) to (9).

4.1.2.Phase – II Synthesis

The conventions followed in Phase – II are provided in Table 1. The input motion in Phase –II is ψ_{23} . The slider displacement is given by X_{23} .

Writing the loop closure equation with reference to Figure 1.2.

$$Z_5 + Z_6 + Z_7 e^{i\gamma_{12}} - Z_9 e^{i\beta_{12}} = 0 \quad (10)$$

After giving the input rotation of ψ_{23} ,

$$Z_5 + Z_6 e^{i\psi_{23}} + Z_7 e^{i\gamma_{12} + \psi_{23}} - Z_9 e^{i\beta_{12}} \rho_{23} = 0 \quad (11)$$

$$\text{Where } \rho_{23} = \frac{Z_9 e^{i\beta_{12}} + X_{23}}{Z_9 e^{i\beta_{12}}} \text{ is the stretch ratio} \quad (12)$$

Subtracting the equation (11) from (12)



$$Z_6 (e^{i\gamma_{23}} - 1) + Z_7 e^{i\gamma_{12}} (e^{i\gamma_{23}} - 1) - Z_9 e^{i\beta_{12}} (\rho_{23} - 1) = 0 \quad (13)$$

$$Z_{10} = Z_5 + Z_6 \quad (14)$$

The coupler motion parameters γ_{23} and X_{23} are prescribed and $Z_7 e^{i\gamma_{12}}$, $Z_9 e^{i\beta_{12}}$, and Z_{10} are retained from Phase-I. Here, in this case, the number of unknowns is 3 and the number of scalar equations is 2, hence number of free choices will be $(3 - 2 = 1)$. The solution space will be ∞^1 . Ψ_{23} will be prescribed and the value of Z_6 and Z_5 are found out by the equations (13) & (14).

4.2.Path Generation with prescribed timing

In case of path generation; a point on a floating link has to be guided along a prescribed path [17]. If this path is correlated with the input link or time then it is called a path generation with prescribed timing. To achieve this, the position of input link and the location of a tracer point on the coupler is part of the design specification.

The difference between motion generation and path generation is that, in motion generation, the designer is concentrating on both position and orientation of the coupler link in the plane, whereas in path generation designer is concentrating only on a path of the point on the coupler.

4.2.1. Phase – I synthesis

In this problem, the input crank motion ϕ_{12}, γ_{12} , and displacement vector d_{12} are provided. The same dyad equations (1) to (6) can be used for this also. Now the Z_2 , ϕ_{12} , Z_8 , and Z_9 are free choices. By the same condition used in the motion generation task, the angle β_{12} and one coordinate of Z_2 , Z_8 , Z_9 vectors are to be free choices. Consequently there will be ∞^4 number of solutions. Z_1 , Z_{10} , Z_3 , Z_4 , X_{12} , and Z_7 are to be found out by the equations (1) to (9).

4.2.2. Phase – II Synthesis

The input crank motion Ψ_{23} and the coupler motion parameter X_{23} are prescribed and $Z_7 e^{i\gamma_{12}}$, $Z_9 e^{i\beta_{12}}$, and Z_{10} are retained from Phase-I. The coupler motion angle γ_{23} is the free choice. Hence, there will be ∞^1 number of solutions.

The value of Z_6 and Z_5 are found out by the equations (10) to (14).

4.3.Function generation

A function generator is a linkage in which the relative movement between the output link and input link of the mechanism accomplish to do the desired task^[17]. It does not require a path tracer point of the coupler link. Here input and output motions must be correlated.

4.3.1.Phase – I synthesis

In this case, the follower Z_4 or β_{12} is a function of input crank motion ϕ_{12} . The same dyad equations (1) to (6) are used to determine the link lengths of the mechanism in Phase I. Here, β_{12} , Z_7 , γ_{12} and ϕ_{12} are prescribed parameters. By the same condition used in motion generation task, vector Z_4 , α_{12} and one coordinate of Z_2 , Z_8 vectors are to be free choices. Consequently there will be ∞^5 number of solutions. Displacement vector d_{12} and other vectors Z_3 , Z_4 , X_{12} , Z_1 and Z_{10} are to be found out by the equations (1) to (9).

4.3.2.Phase – II Synthesis

The input crank motion Ψ_{23} and output motion X_{23} are prescribed. $Z_7 e^{i\gamma_{12}}$, $Z_9 e^{i\beta_{12}}$ and Z_{10} are retained from Phase-I. The coupler motion angle γ_{23} is the free choice. Hence, there will be ∞^1 number of solutions. The value of Z_6 and Z_5 are found out by the equations (10) to (14).

Table 2: Solution space of the mechanism in all types of dimensional synthesis

Description	Phase I	Phase II
a) Motion generation		
Link fixed temporarily	O_cC (Z_6)	O_aA (Z_2)
Prescribed parameters	α_{12} , γ_{12} , d_{12} $\beta_{12} = 180^\circ - 2 \mu_{\min}$	γ_{23} and X_{23}
Free choices made	Z_2 , ϕ_{12} , Z_8 and Z_9	Ψ_{23}
Unknowns	Z_3 , Z_4 , X_{12} , Z_1 , Z_{10} , and Z_7	Z_6 and Z_5
No. of solutions.	∞^4	∞^1



Total Number of solutions.	∞^5	
b) Path generation with prescribed timings		
Link fixed temporarily	O _c C (Z ₆)	O _a A (Z ₂)
Prescribed parameters	$\phi_{12}, \gamma_{12}, d_{12}$ $\beta_{12} = 180^\circ - 2 \mu_{\min}$	γ_{23} and X ₂₃
Free choices made	Z ₂ , α_{12} , Z ₈ and Z ₉	Ψ_{23}
Unknowns	Z ₃ , Z ₄ , X ₁₂ , Z ₁ , Z ₁₀ , and Z ₇	Z ₆ and Z ₅
No. of solutions.	∞^4	∞^1
Total Number of solutions.	∞^5	
c) Function generation		
Link fixed temporarily	O _c C (Z ₆)	O _a A (Z ₂)
Prescribed parameters	$\beta_{12}, Z_7, \gamma_{12},$ and ϕ_{12}	Ψ_{23} and X ₂₃
Free choices made	Z ₄ , α_{12} , Z ₂ and Z ₈	γ_{23}
Unknowns	Z ₃ , Z ₄ , X ₁₂ , Z ₁ , and Z ₁₀	Z ₆ and Z ₅
No. of solutions	∞^5	∞^1
Total Number of solutions	∞^6	

CONCLUSIONS

The proposed technique is for the seven-link slider mechanism operating between the two extreme positions. This method is to synthesize the higher DOF mechanism reducing it to a single DOF mechanism in each phase. The method is simple and can perform multiple tasks with single mechanism for higher DOF also. This method reduces the solution space with no iteration.

EXAMPLES

The simplicity of the technique will be acknowledged by accompanying below example.

Example: It is required to synthesize the planar 7-bar mechanism for AFP with VTM as in Figure 1.0. Provided that coupler parameters $d_{12} = -32.278 - i \times 36.97$, $\alpha_{12} = 62^\circ$ CW. $\gamma_{12} = 60^\circ$ CCW



Solution: Consider the mechanism to operate in two phases as shown in Figure 1.1& 1.2.

In Phase I the mechanism operate between extreme positions. The transmission angle is in the range of

$$60^\circ \leq \mu \leq 180^\circ.$$

Let $\mu_{\min} = 62^\circ$, From Figure 1.2, $\beta_{12} = 180^\circ - 2 \times \mu_{\min} = 180 - 2 \times 62 = 56^\circ$

Let be consider the condition that the displacement vector d_{12} and input vector Z_2 are inline. Then by the vector algebra,

The angle of vector $d_{12} = \text{Angle of Vector } Z_2$

$$\text{i.e., } \tan^{-1} \left(\frac{\delta_{12Y}}{\delta_{12X}} \right) = \tan^{-1} \left(\frac{Z_{2Y}}{Z_{2X}} \right)$$

$$\frac{\delta_{12Y}}{\delta_{12X}} = \frac{Z_{2Y}}{Z_{2X}}$$

Since d_{12} are already prescribed and if one coordinate of Z_2 is assumed then above equation gives another coordinate. Let assume $Z_{2x} = 19.702$ as a free choice. Then

$$Z_{2y} = \frac{36.97}{32.278} \times 19.702 = 22.565$$

Hence $Z_2 = 19.702 + ix \ 22.565$

From equation (1)

$$Z_3 = \frac{\delta_{12} - Z_2 (e^{i\alpha_{12}} - 1)}{(e^{i\alpha_{12}} - 1)}$$

By substituting the known values,

$$Z_3 = 23.5137 + ix \ 25.888$$

From equation (2)

$$Z_4 = \frac{\delta_{12}}{(e^{i\beta_{12}} - 1)}$$

$$Z_4 = -17.906 + ix \ 48.2093$$

Similarly, vector $Z_4, Z_8,$ and z_9 are inline.

So,
$$\tan^{-1} (Z_{4y} / Z_{4x}) = \tan^{-1} (Z_{8y} / Z_{8x})$$

Let assume the real coordinate of Z_8 i.e $Z_{8x} = -3.5$



Then by the above formula
$$Z_{8Y} = \frac{Z_{4Y}}{Z_{4X}} Z_{8X}$$

$$Z_{8y} = 9.372$$

Similarly assuming the real coordinate of Z_9 i. e. $Z_{9x} = -13.956$

Then
$$\tan^{-1} (Z_{4y} / Z_{4x}) = \tan^{-1} (Z_{9y} / Z_{9x})$$

$$Z_{9Y} = \frac{Z_{4Y}}{Z_{4X}} Z_{9X}$$

$$Z_{9y} = 37.486$$

Hence, $Z_8 = -3.5 + ix 9.372$ and $Z_9 = -13.956 + ix 37.486$

Substituting these values in equation (3) we get $X_{12} = -35.539 -ix 0.66$

Now, from equation (4)
$$Z_7 = \frac{X_{12}}{(e^{i\gamma_{12}} - 1)}$$

$$Z_7 = 17.197 + i x 31.1076$$

From equation (5) & (6) $Z_1 = 61.1217 + ix 0.0002437 \approx 61.1217$ &

$$Z_{10} = -20.697 - i x 21.735$$

Phase – II

Given $X_{23} = 29.27 - i x 6.579$, $\gamma_{23} = 25^\circ$ CW. and retaining the values of vectors from phase I.

stretch ratio
$$\rho_{23} = \frac{Z_9 e^{i\beta_{12}} + X_{23}}{Z_9 e^{i\beta_{12}}}$$

$$\rho_{23} = 0.2499$$

From equation (9)
$$Z_6 = \frac{Z_9 e^{i\beta_{12}} (\rho_{23} - 1) - Z_7 e^{i\gamma_{12}} (e^{i\gamma_{23}} - 1)}{(e^{i\gamma_{23}} - 1)}$$

$$Z_6 = -19.622 - i x 10.0147$$

And
$$Z_5 = Z_{10} - Z_6$$

$$Z_5 = -1.116 - ix 11.6893$$

At the end of Phase II, the determined links of the mechanism are as follows:



Table 3: Overall dimensions and their orientations of all links of the mechanism

Sl. No.	Vector	Position	Magnitude	Angle measured by + ve X-axis CCW
1	Z_1	61.127	61.127	0°
2	Z_2	$19.702 + ix 22.565$	29.98	48.87°
3	Z_3	$23.513 + ix 25.888$	34.976	48.75°
4	Z_4	$-17.906 + ix 48.2093$	51.427	110.38°
5	Z_5	$-1.116 - ix 10.0147$	11.742	264.54°
6	Z_6	$-19.622 - ix 10.0147$	22.029	207.03°
7	Z_7	$17.197 + ix 31.107$	35.544	61.065°
8	Z_8	$-3.5 + ix 9.372$	10.00	110.38°
9	Z_9	$-13.956 + ix 37.486$	40	110.38°
10	Z_{10}	$-20.697 - ix 21.735$	30.012	6.4°

APPLICATION OF VTM IN AUTOMATIC FIBER REPLACEMENT MECHANISM

The below example narrates the application of proposed method in Automated Fiber Placement (AFP). In this process, the number of resin-impregnated fibers is fed into the fiber placement head based on the mould surface. These fibers are pulled from the creel and fed to the CCR unit. In the CCR unit, the fibers are going to cut at the particular size and then these are laid onto the mandrel with radiation and compacted to the mold surface by compacting process as shown in Figure.1.3. By connecting knife blade and clamping block, Cutting and clamping operations are processed.

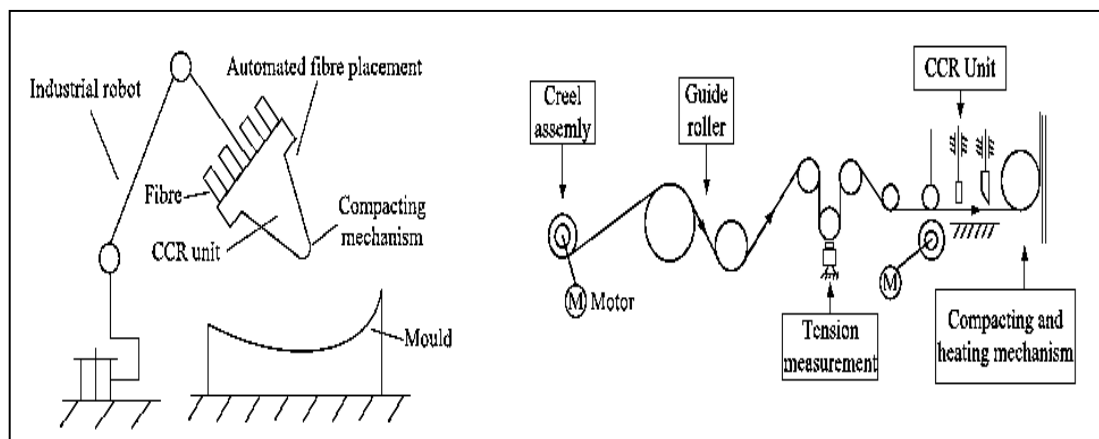


Fig.1.3: Schematic diagram of Automated Fiber Placement machine^[18].



A variable topology mechanism is introduced to perform the cutting, clamping, and restarting operations as shown in Figure.1.4. O_aO_b and O_bO_c are permanent links and L shaped link BE which is hinged at O_b is used to engage and disengage the tow. As shown in Figure 1.1 in Phase – I, the slider D will be slide along with the link O_bB and draws the tow into the mould surface. In Phase – II, as shown in Figure 1.2, the slider will move from position D_2 to D_3 now to toes are cut and to lay down onto mould with compacting and cutting edge connected to it. This process will leads to automatic fabrication of composites fibre placement method.

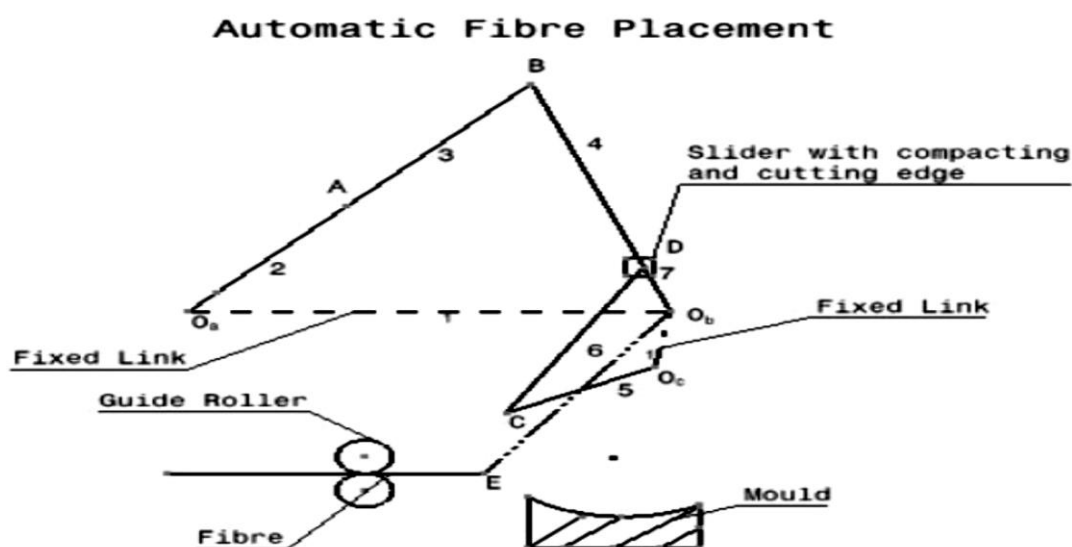


Fig.1.4. Proposed 7 bar slider variable topology mechanism



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