Approximate Dimensional Synthesis of Watt-I Mechanism based on Twenty Precision Points Path Generation

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Abstract – In this paper, a six-bar, single degree of freedom, Watt-I mechanism has been dimensionally synthesized to solve the problem of path generation. The mechanism consists of revolute pairs and is capable to trace the prescribed path which comprises of twenty precision points. In the synthesis process, the standard dyad/triad and analytical loop closure equations are generated in terms of complex number mathematics. A MATLAB code is used to solve these equations for twenty coupler displacement positions and determine the lengths and orientations of various links of the mechanism. The overall dimensional synthesis of Watt-I mechanism has been demonstrated on a numerical example. SAM application software is also employed to verify the results.

Index Terms – Dimensional Synthesis, Path Generation, Precision Points, Watt-I Mechanism

1. INTRODUCTION

Dimensional synthesis of planar mechanisms is an important step to design machines for industrial applications. It involves determination of major dimensions of various links of the mechanism to fulfill the required kinematic task. The envisageable mechanism may have four, six or even higher number of links. It may also be a slider crank mechanism or any other type of mechanism whose dimensions are to be determined. Depending upon the requirement, the kinematic task may be function generation, path generation, motion generation or rigid body guidance etc. The principal dimensions implicate determination of link lengths along with their angular orientations, position of pivots and displacement between extreme positions of slider of the mechanism. Researchers have performed dimensional synthesis of mechanisms using graphical as well as analytical techniques. The graphical methods were prevalent till starting of 20th century second-half [1, 2]. These methods have limitation of drawing accuracy. On the other hand, when analytical methods are used along with high-end programming software, they provide benefits of improved accuracy, easy of application, simplicity and generality. Based on analytical techniques, the dimensional synthesis of various mechanisms have been carried out by various researchers for different standard kinematic tasks viz., function generation, motion generation and path generation.

2. RELATED WORK

The dimensional synthesis of five-bar mechanism based on graphical methods was carried on by Rose and Rawat [1-2]. The synthesis of an adjustable four bar mechanism was suggested by Naik and Amarnath [3]. They employed five bar loop closure equations for function generators in their work. The synthesis of planar five-bar mechanism with variable topology for motion between extreme positions was projected by Balli and Chand [4-5] using complex number mathematics. Later, the synthesis of this mechanism was extended to the five-bar mechanism that consisted of two binary links having offset tracing points [6-7]. The synthesis of seven-bar mechanisms with variable topology was carried out for motion between extreme positions by various researchers [8-11]. They projected these syntheses for various kinematic tasks viz., function generation, motion generation and path generation. Furthermore, the syntheses of five-bar slider mechanisms and seven-bar slider mechanisms with variable topology were jointly performed for finitely separated positions by Daivagna and Balli [12-14].

The synthesis of single degree of freedom six-bar mechanisms was carried out by different researchers [15-17] upto a certain number of precision points. E.g., The path generation dimensional synthesis of six-bar mechanism was performed only upto 8 precision points [15]. Later, the work was extended upto 12 and 15 precision points [16-17]. The mechanisms with higher number of precision points are required to follow the complicated shapes and paths needed in industrial automation. Therefore, in present work, dimensional synthesis of a six-bar Watt I mechanism that traces a trajectory defined by twenty precision points has been performed. The analytical loop closure equations have been generated for different dyads and triads using complex number mathematics. Moreover, a numerical problem has been solved to demonstrate the synthesis of given mechanism. Finally, the solution is verified using SAM software.

3. CONFIGURATION OF SIX-BAR WATT-I MECHANISM

A Watt-I is a six-bar mechanism. It consists of two ternary links and four binary links. In Watt-II mechanism, the fixed link is a binary link. The ternary links forms revolute pair at common intersection joint position. One binary link of the Watt-I mechanism has an offset.

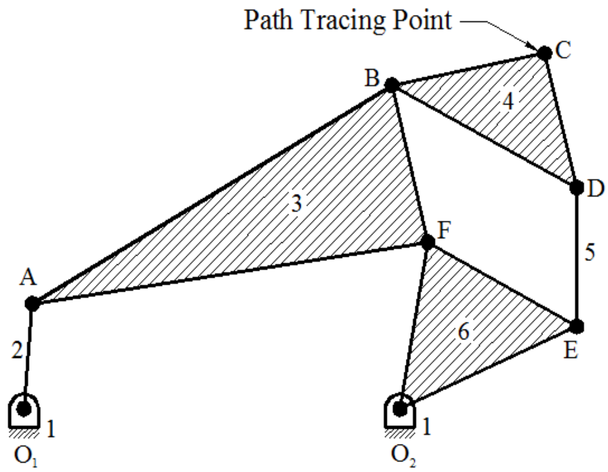

Figure 1 Configuration of Six-bar Watt-I mechanism

The configuration of Six-bar Watt-I mechanism is shown in Figure 1. The link 1 is binary link which is fixed at pivots O_1 and O_2. The link 2 acts as a crank which rotates about fixed point O_1. The input motion is supplied to the mechanism through link 2. The link 3 is a ternary link, which is connected with other links at 3 points, A, B and F. The link 4 is a binary link with an offset at point C which is the tracing point of the mechanism for which it is dimensionally synthesized. There is another ternary link 6, which is connected with other links at 3 points, O_2, E and F. The link 6 oscillates about fixed point O_2. The link 4 and link 6 are connected by means of a binary link 5 at points D and E respectively.

4. GENERATION OF LOOP CLOSURE EQUATIONS

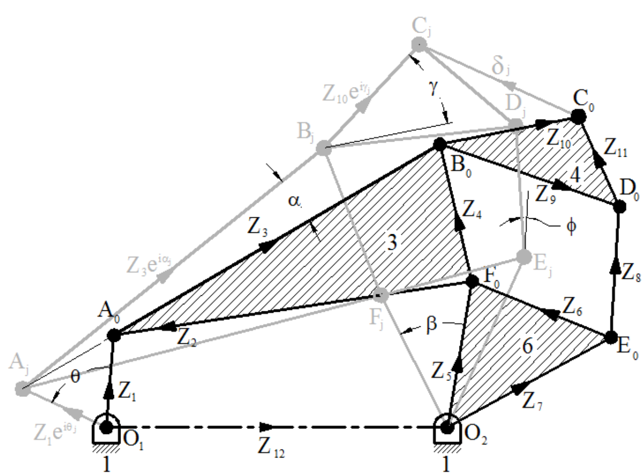

Figure 2 Six-bar Watt-I mechanism displaced from home to prime position by δ_j

Consider the initial arrangement of the given Six-bar Watt-I mechanism expressed by joint positions $O_1A_0B_0C_0D_0E_0F_0O_2$. When the crank O_1A_0 rotates through angle θ and reaches position O_1A_j, the joint positions of remaining links are also shifted and prime position of the linkage is expressed by $O_1A_jB_jC_jD_jE_jF_jO_2$ as shown in Figure 2. The displacement of tracing point from position C_0 to C_j is expressed by δ_j. The derivation of loop closure equations for 20 precision points is explained below:

Writing the loop closure equation [18] for independent vector loop $O_1A_jB_jC_jC_0B_0A_0O_1$ (Refer figure 2)

$$Z_1e^{i\theta_j} + Z_3e^{i\alpha_j} + Z_{10}e^{i\gamma_j} - \delta_j - Z_{10} - Z_3 - Z_1 = 0$$

$$Z_1(e^{i\theta_j} - 1) + Z_3(e^{i\alpha_j} - 1) + Z_{10}(e^{i\gamma_j} - 1) = \delta_j \quad (1)$$

Writing the loop closure equation [18] for independent vector loop $O_2E_jD_jC_jC_0D_0E_0O_2$ (Refer figure 2)

$$Z_7e^{i\beta_j} + Z_8e^{i\varphi_j} + Z_{11}e^{i\gamma_j} - \delta_j - Z_{11} - Z_8 - Z_7 = 0$$

$$Z_7(e^{i\beta_j} - 1) + Z_8(e^{i\varphi_j} - 1) + Z_{11}(e^{i\gamma_j} - 1) = \delta_j \quad (2)$$

Writing the loop closure equation [18] for independent vector loop $E_0F_0B_0D_0E_0$ (Refer figure 2)

$$Z_6 + Z_4 + Z_9 - Z_8 = 0 \quad (3a)$$

Writing the loop closure equation [18] for independent vector loop $E_jF_jB_jD_jE_j$ (Refer figure 2)

$$Z_6e^{i\beta_j} + Z_4e^{i\alpha_j} + Z_9e^{i\gamma_j} - Z_8e^{i\varphi_j} = 0 \quad (3b)$$

Subtracting equation (3a) from equation (3b), we get

$$Z_6(e^{i\beta_j} - 1) + Z_4(e^{i\alpha_j} - 1) + Z_9(e^{i\gamma_j} - 1) - Z_8(e^{i\varphi_j} - 1) = 0 \quad (3)$$

In equations (1) to (3), value of j varies from 1 to 20 for twenty points comprising the required trajectory.

Considering closed loop $F_0A_0B_0F_0$, we get unknown vector Z_2 (Refer figure 2)

$$Z_2 = Z_4 - Z_3 \quad (4)$$

Considering closed loop $O_2F_0E_0O_2$, we get unknown vector Z_5 (Refer figure 2)

$$Z_5 = Z_6 + Z_7 \quad (5)$$

Considering closed loop $O_1O_2F_0A_0O_1$, we get unknown vector Z_{12} (Refer figure 2)

$$Z_{12} = Z_1 - Z_2 - Z_5 \quad (6)$$

5. NUMERICAL PROBLEM BASED ON SYNTHESIS OF SIX-BAR WATT-I MECHANISM

5.1. Problem Statement

It is required to synthesize a six-bar Watt-I mechanism which transmits motion along a path prescribed by twenty precision points (Refer figure 3) P_1 (0.950, 0.941), P_2 (0.886, 0.935), P_3 (0.838, 0.925), P_4 (0.809, 0.915), P_5 (0.801, 0.906), P_6 (0.816, 0.897), P_7 (0.857, 0.888), P_8 (0.927, 0.875), P_9 (1.027, 0.851), P_{10} (1.152, 0.805), P_{11} (1.280, 0.732), P_{12} (1.378, 0.655), P_{13} (1.423, 0.621), P_{14} (1.426, 0.645), P_{15} (1.400, 0.703), P_{16} (1.351, 0.771), P_{17} (1.283, 0.836), P_{18} (1.202, 0.887), P_{19} (1.114, 0.921) and P_{20} (1.028, 0.938).

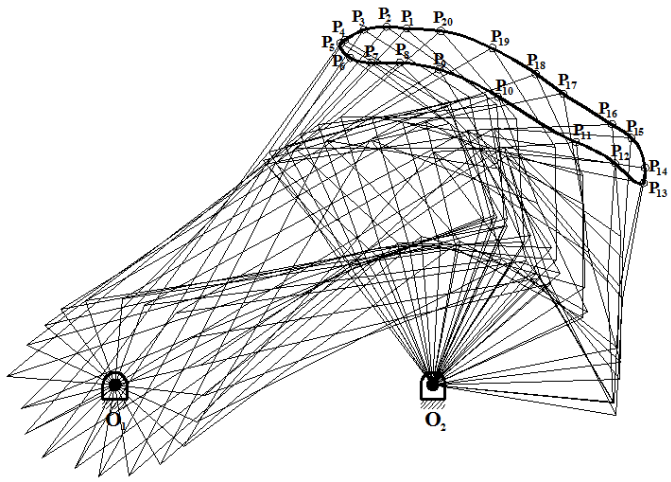

Figure 3 Mobility of Six-bar Watt-I linkage from initial position to 20 displaced positions

5.2. Prescribed Parameters

The prescribed parameters are displacement of each point from initial position i.e. $\delta_j = P_j - P_1$ at equal intervals of θ_j {0, 2π} (where j = 1, 2,...20).

5.3. Assumed Parameters

The parameters assumed freely are θ_j, α_j, β_j, γ_j and ϕ_j. The range of these parameters are α_j {-2π/45, 5π/36}, β_j {-5π/12, π/18}, γ_j {-π/3, π/18} and ϕ_j {-π/18, π/6} [19].

5.4. Design Parameters

The MATLAB code is developed to solve for the design vectors Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9, Z_{10}, Z_{11} and Z_{12}.

6. SOLUTION OF LOOP CLOSURE EQUATIONS

The solution of equations (1) to (6) is difficult to find manually for twenty precision points. Also, the number of equations is more than the number of unknowns, so a code is developed in MATLAB to solve these equations. To obtain solution, MATLAB algorithm consists of following steps:

Step1. Read the value of twenty precision points coordinates.

Step2. Calculate displacement (δ_j) for each point by subtracting its coordinates from initial point.

Step3. Read the values of all free parameters and assumed parameters.

Step4. Calculate values $e^{i\theta_j}$, $e^{i\alpha_j}$, $e^{i\beta_j}$, $e^{i\gamma_j}$ and $e^{i\varphi_j}$ for j = 1, 2, 3,......20.

Step5. Calculate design vectors Z_1, Z_3 and Z_{10} using equation (1).

Step6. Calculate design vectors Z_7, Z_8 and Z_{11} using equation (2).

Step7. Calculate design vectors Z_6, Z_4 and Z_9 using equation (3).

Step8. Calculate design vector Z_2 using equation (4).

Step9. Calculate design vector Z_5 using equation (5).

Step10. Calculate design vector Z_{12} using equation (6).

7. RESULTS AND DISCUSSIONS

The dimensions and orientations of various link lengths obtained by solving loop closure equations using MATLAB code are:

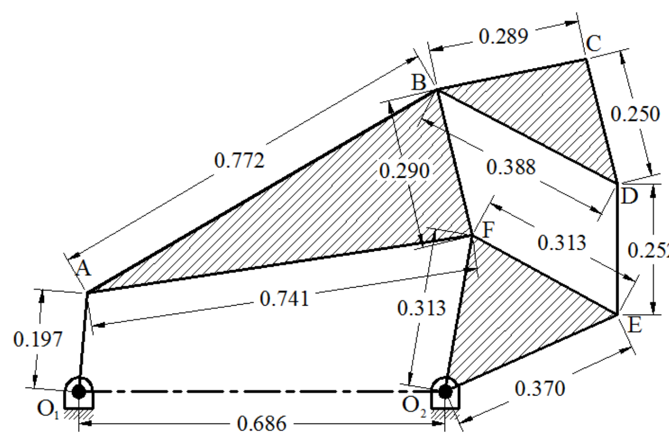

Figure 4 Graphical representation of the final dimensions of each link of six-bar Watt-I mechanism based on twenty precision points path generation

Z_1 = 0.197 m ∠ 157.22º; Z_2 = 0.741 m ∠15.41º; Z_3 = 0.772 m ∠37.36º; Z_4 = 0.290 m ∠110.52º; Z_5 = 0.313 m ∠119.35º; Z_6 = 0.313 m ∠11.80º; Z_7 = 0.370 ∠245.57º; Z_8 = 0.252 m ∠95.17º; Z_9 = 0.388 m ∠6.42º; Z_{10} = 0.289 m ∠46.47º; Z_{11} = 0.250 m ∠138.37º; Z_{12} = 0.686 m ∠0.27º.

The final dimensions of each link of Six-bar Watt-I mechanism based on twenty precision points path generation are graphically shown in Figure 4.

8. CONCLUSIONS

The present work suggests dimensional synthesis of a Six-bar Watt-I mechanism that transmits motion for a specified path prescribed by twenty precision points. The results have been verified using SAM software and signify the effectiveness of the proposed method. The present work augments the requirements of automation industry and will facilitate in the invention of useful mechanism. These mechanisms will be effective in tracing complicated paths based on higher number of precision points. This technique offers reduced solution space with increased accuracy and overcome the drawback of graphical techniques of limited accuracy. The solution obtained is consistent with kinematic tasks of path generation and can be further extended for other standard kinematic tasks of motion generation and function generation.

NOMENCLATURE

Z_i : Length of each side of all of links (i = 1, 2, 3,...12)

δ_j : Displacement of tracing point from position C_0 to C_j (j = 1, 2,...20)

θ_j : Angle through which crank O_1A_0 rotates and reaches at position O_1A_j

α_j : Angle through which ternary link $A_0B_0F_0$ rotates and reaches at position $A_jB_jF_j$

β_j : Angle through which ternary link $O_2E_0F_0$ rotates and reaches at position $O_2E_jF_j$

γ_j : Angle through which binary offset link $B_0C_0D_0$ rotates and reaches at position $B_jC_jD_j$

ϕ_j : Angle through which binary link D_0E_0 rotates and reaches at position D_jE_j

APPENDIX

The loop closure equation (1) for Six bar Watt- I mechanism is $Z_1(e^{i\theta_j} -1) + Z_3(e^{i\alpha_j} -1) + Z_{10}(e^{i\gamma_j} -1) = \delta_j$ for twenty precision points, say (j = 1, 2………..20).

The above equation can be formulated in the form as

$$Z_1(e^{i\theta_1} -1) + Z_3(e^{i\alpha_1} -1) + Z_{10}(e^{i\gamma_1} -1) = \delta_1 \quad (7)$$

$$Z_1(e^{i\theta_2} -1) + Z_3(e^{i\alpha_2} -1) + Z_{10}(e^{i\gamma_2} -1) = \delta_2 \quad (8)$$

$$Z_1(e^{i\theta_3} -1) + Z_3(e^{i\alpha_3} -1) + Z_{10}(e^{i\gamma_3} -1) = \delta_3 \quad (9)$$

$$Z_1(e^{i\theta_4} -1) + Z_3(e^{i\alpha_4} -1) + Z_{10}(e^{i\gamma_4} -1) = \delta_4 \quad (10)$$

$$Z_1(e^{i\theta_5} -1) + Z_3(e^{i\alpha_5} -1) + Z_{10}(e^{i\gamma_5} -1) = \delta_5 \quad (11)$$

$$Z_1(e^{i\theta_6} -1) + Z_3(e^{i\alpha_6} -1) + Z_{10}(e^{i\gamma_6} -1) = \delta_6 \quad (12)$$

$$Z_1(e^{i\theta_7} -1) + Z_3(e^{i\alpha_7} -1) + Z_{10}(e^{i\gamma_7} -1) = \delta_7 \quad (13)$$

$$Z_1(e^{i\theta_8} -1) + Z_3(e^{i\alpha_8} -1) + Z_{10}(e^{i\gamma_8} -1) = \delta_8 \quad (14)$$

$$Z_1(e^{i\theta_9} -1) + Z_3(e^{i\alpha_9} -1) + Z_{10}(e^{i\gamma_9} -1) = \delta_9 \quad (15)$$

$$Z_1(e^{i\theta_{10}} -1) + Z_3(e^{i\alpha_{10}} -1) + Z_{10}(e^{i\gamma_{10}} -1) = \delta_{10} \quad (16)$$

$$Z_1(e^{i\theta_{11}} -1) + Z_3(e^{i\alpha_{11}} -1) + Z_{10}(e^{i\gamma_{11}} -1) = \delta_{11} \quad (17)$$

$$Z_1(e^{i\theta_{12}} -1) + Z_3(e^{i\alpha_{12}} -1) + Z_{10}(e^{i\gamma_{12}} -1) = \delta_{12} \quad (18)$$

$$Z_1(e^{i\theta_{13}} -1) + Z_3(e^{i\alpha_{13}} -1) + Z_{10}(e^{i\gamma_{13}} -1) = \delta_{13} \quad (19)$$

$$Z_1(e^{i\theta_{14}} -1) + Z_3(e^{i\alpha_{14}} -1) + Z_{10}(e^{i\gamma_{14}} -1) = \delta_{14} \quad (20)$$

$$Z_1(e^{i\theta_{15}} -1) + Z_3(e^{i\alpha_{15}} -1) + Z_{10}(e^{i\gamma_{15}} -1) = \delta_{15} \quad (21)$$

$$Z_1(e^{i\theta_{16}} -1) + Z_3(e^{i\alpha_{16}} -1) + Z_{10}(e^{i\gamma_{16}} -1) = \delta_{16} \quad (22)$$

$$Z_1(e^{i\theta_{17}} -1) + Z_3(e^{i\alpha_{17}} -1) + Z_{10}(e^{i\gamma_{17}} -1) = \delta_{17} \quad (23)$$

$$Z_1(e^{i\theta_{18}} -1) + Z_3(e^{i\alpha_{18}} -1) + Z_{10}(e^{i\gamma_{18}} -1) = \delta_{18} \quad (24)$$

$$Z_1(e^{i\theta_{19}} -1) + Z_3(e^{i\alpha_{19}} -1) + Z_{10}(e^{i\gamma_{19}} -1) = \delta_{19} \quad (25)$$

$$Z_1(e^{i\theta_{20}} -1) + Z_3(e^{i\alpha_{20}} -1) + Z_{10}(e^{i\gamma_{20}} -1) = \delta_{20} \quad (26)$$

The loop closure equation (2) for Six bar Watt- I mechanism is $Z_7(e^{i\beta_j} -1) + Z_8(e^{i\varphi_j} -1) + Z_{11}(e^{i\gamma_j} -1) = \delta_j$ for twenty precision points, say (j = 1, 2………..20).

The above equation can be formulated in the form as

$$Z_7(e^{i\beta_1} -1) + Z_8(e^{i\varphi_1} -1) + Z_{11}(e^{i\gamma_1} -1) = \delta_1 \quad (27)$$

$$Z_7(e^{i\beta_2} -1) + Z_8(e^{i\varphi_2} -1) + Z_{11}(e^{i\gamma_2} -1) = \delta_2 \quad (28)$$

$$Z_7(e^{i\beta_3} -1) + Z_8(e^{i\varphi_3} -1) + Z_{11}(e^{i\gamma_3} -1) = \delta_3 \quad (29)$$

$$Z_7(e^{i\beta_4} -1) + Z_8(e^{i\varphi_4} -1) + Z_{11}(e^{i\gamma_4} -1) = \delta_4 \quad (30)$$

$$Z_7(e^{i\beta_5} -1) + Z_8(e^{i\varphi_5} -1) + Z_{11}(e^{i\gamma_5} -1) = \delta_5 \quad (31)$$

$$Z_7(e^{i\beta_6} -1) + Z_8(e^{i\varphi_6} -1) + Z_{11}(e^{i\gamma_6} -1) = \delta_6 \quad (32)$$

$$Z_7(e^{i\beta_7} -1) + Z_8(e^{i\varphi_7} -1) + Z_{11}(e^{i\gamma_7} -1) = \delta_7 \quad (33)$$

$$Z_7(e^{i\beta_8} -1) + Z_8(e^{i\varphi_8} -1) + Z_{11}(e^{i\gamma_8} -1) = \delta_8 \quad (34)$$

$$Z_7(e^{i\beta_9}-1)+Z_8(e^{i\varphi_9}-1)+Z_{11}(e^{i\gamma_9}-1)=\delta_9 \quad (35)$$

$$Z_7(e^{i\beta_{10}}-1)+Z_8(e^{i\varphi_{10}}-1)+Z_{11}(e^{i\gamma_{10}}-1)=\delta_{10} \quad (36)$$

$$Z_7(e^{i\beta_{11}}-1)+Z_8(e^{i\varphi_{11}}-1)+Z_{11}(e^{i\gamma_{11}}-1)=\delta_{11} \quad (37)$$

$$Z_7(e^{i\beta_{12}}-1)+Z_8(e^{i\varphi_{12}}-1)+Z_{11}(e^{i\gamma_{12}}-1)=\delta_{12} \quad (38)$$

$$Z_7(e^{i\beta_{13}}-1)+Z_8(e^{i\varphi_{13}}-1)+Z_{11}(e^{i\gamma_{13}}-1)=\delta_{13} \quad (39)$$

$$Z_7(e^{i\beta_{14}}-1)+Z_8(e^{i\varphi_{14}}-1)+Z_{11}(e^{i\gamma_{14}}-1)=\delta_{14} \quad (40)$$

$$Z_7(e^{i\beta_{15}}-1)+Z_8(e^{i\varphi_{15}}-1)+Z_{11}(e^{i\gamma_{15}}-1)=\delta_{15} \quad (41)$$

$$Z_7(e^{i\beta_{16}}-1)+Z_8(e^{i\varphi_{16}}-1)+Z_{11}(e^{i\gamma_{16}}-1)=\delta_{16} \quad (42)$$

$$Z_7(e^{i\beta_{17}}-1)+Z_8(e^{i\varphi_{17}}-1)+Z_{11}(e^{i\gamma_{17}}-1)=\delta_{17} \quad (43)$$

$$Z_7(e^{i\beta_{18}}-1)+Z_8(e^{i\varphi_{18}}-1)+Z_{11}(e^{i\gamma_{18}}-1)=\delta_{18} \quad (44)$$

$$Z_7(e^{i\beta_{19}}-1)+Z_8(e^{i\varphi_{19}}-1)+Z_{11}(e^{i\gamma_{19}}-1)=\delta_{19} \quad (45)$$

$$Z_7(e^{i\beta_{20}}-1)+Z_8(e^{i\varphi_{20}}-1)+Z_{11}(e^{i\gamma_{20}}-1)=\delta_{20} \quad (46)$$

The loop closure equation (3) for Six bar Watt- I mechanism is $Z_6(e^{i\beta_j}-1)+Z_4(e^{i\alpha_j}-1)+Z_9(e^{i\gamma_j}-1)-Z_8(e^{i\varphi_j}-1)=0$ for twenty precision points, say (j = 1, 2………..20).

The above equation can be formulated in the form as

$$Z_6(e^{i\beta_1}-1)+Z_4(e^{i\alpha_1}-1)+Z_9(e^{i\gamma_1}-1)-Z_8(e^{i\varphi_1}-1)=0 \quad (47)$$

$$Z_6(e^{i\beta_2}-1)+Z_4(e^{i\alpha_2}-1)+Z_9(e^{i\gamma_2}-1)-Z_8(e^{i\varphi_2}-1)=0 \quad (48)$$

$$Z_6(e^{i\beta_3}-1)+Z_4(e^{i\alpha_3}-1)+Z_9(e^{i\gamma_3}-1)-Z_8(e^{i\varphi_3}-1)=0 \quad (49)$$

$$Z_6(e^{i\beta_4}-1)+Z_4(e^{i\alpha_4}-1)+Z_9(e^{i\gamma_4}-1)-Z_8(e^{i\varphi_4}-1)=0 \quad (50)$$

$$Z_6(e^{i\beta_5}-1)+Z_4(e^{i\alpha_5}-1)+Z_9(e^{i\gamma_5}-1)-Z_8(e^{i\varphi_5}-1)=0 \quad (51)$$

$$Z_6(e^{i\beta_6}-1)+Z_4(e^{i\alpha_6}-1)+Z_9(e^{i\gamma_6}-1)-Z_8(e^{i\varphi_6}-1)=0 \quad (52)$$

$$Z_6(e^{i\beta_7}-1)+Z_4(e^{i\alpha_7}-1)+Z_9(e^{i\gamma_7}-1)-Z_8(e^{i\varphi_7}-1)=0 \quad (53)$$

$$Z_6(e^{i\beta_8}-1)+Z_4(e^{i\alpha_8}-1)+Z_9(e^{i\gamma_8}-1)-Z_8(e^{i\varphi_8}-1)=0 \quad (54)$$

$$Z_6(e^{i\beta_9}-1)+Z_4(e^{i\alpha_9}-1)+Z_9(e^{i\gamma_9}-1)-Z_8(e^{i\varphi_9}-1)=0 \quad (55)$$

$$Z_6(e^{i\beta_{10}}-1)+Z_4(e^{i\alpha_{10}}-1)+Z_9(e^{i\gamma_{10}}-1)-Z_8(e^{i\varphi_{10}}-1)=0 \quad (56)$$

$$Z_6(e^{i\beta_{11}}-1)+Z_4(e^{i\alpha_{11}}-1)+Z_9(e^{i\gamma_{11}}-1)-Z_8(e^{i\varphi_{11}}-1)=0 \quad (57)$$

$$Z_6(e^{i\beta_{12}}-1)+Z_4(e^{i\alpha_{12}}-1)+Z_9(e^{i\gamma_{12}}-1)-Z_8(e^{i\varphi_{12}}-1)=0 \quad (58)$$

$$Z_6(e^{i\beta_{13}}-1)+Z_4(e^{i\alpha_{13}}-1)+Z_9(e^{i\gamma_{13}}-1)-Z_8(e^{i\varphi_{13}}-1)=0 \quad (59)$$

$$Z_6(e^{i\beta_{14}}-1)+Z_4(e^{i\alpha_{14}}-1)+Z_9(e^{i\gamma_{14}}-1)-Z_8(e^{i\varphi_{14}}-1)=0 \quad (60)$$

$$Z_6(e^{i\beta_{15}}-1)+Z_4(e^{i\alpha_{15}}-1)+Z_9(e^{i\gamma_{15}}-1)-Z_8(e^{i\varphi_{15}}-1)=0 \quad (61)$$

$$Z_6(e^{i\beta_{16}}-1)+Z_4(e^{i\alpha_{16}}-1)+Z_9(e^{i\gamma_{16}}-1)-Z_8(e^{i\varphi_{16}}-1)=0 \quad (62)$$

$$Z_6(e^{i\beta_{17}}-1)+Z_4(e^{i\alpha_{17}}-1)+Z_9(e^{i\gamma_{17}}-1)-Z_8(e^{i\varphi_{17}}-1)=0 \quad (63)$$

$$Z_6(e^{i\beta_{18}}-1)+Z_4(e^{i\alpha_{18}}-1)+Z_9(e^{i\gamma_{18}}-1)-Z_8(e^{i\varphi_{18}}-1)=0 \quad (64)$$

$$Z_6(e^{i\beta_{19}}-1)+Z_4(e^{i\alpha_{19}}-1)+Z_9(e^{i\gamma_{19}}-1)-Z_8(e^{i\varphi_{19}}-1)=0 \quad (65)$$

$$Z_6(e^{i\beta_{20}}-1)+Z_4(e^{i\alpha_{20}}-1)+Z_9(e^{i\gamma_{20}}-1)-Z_8(e^{i\varphi_{20}}-1)=0 \quad (66)$$

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