KINEMATIC ANALYSIS AND SIMULATION OF TWO-LEGGED THEO-JANSEN'S MECHANISM

A project report submitted

in partial fulfillment of the requirement for the award of the degree of

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IN
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by

K.JYOTSHNA	**(314126520080)**
M.VIJUSHA	**(314126520090)**
S.SUNEETHA	**(314126520142)**
N.DINESH SRINIVASA RAO	**(314126520105)**
S.SHREEJI	**(314126520143)**

Under the esteemed guidance of

Sri. R. CHANDRAMOULI, M.TECH
(ASSOCIATE PROFESSOR)
Department of Mechanical Engineering

PRAGNANAM BRAHMA
ANITS

DEPARTMENT OF MECHANICAL ENGINEERING
ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES
(Approved by AICTE, Permanently Affiliated to A.U., & Accredited by NBA and NAAC with 'A' Grade)
Sangivalasa, Bheemunipatnam Mandal,
VISAKHAPATNAM-531162

ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY &SCIENCES

(Autonomous)

(Approved by AICTE, Permanently Affiliated to A.U., &
Accredited by NBA and NAAC with 'A' Grade)

PRAGNANAM BRAHMA

ANITS

CERTIFICATE

This is to certify that the project report entitled **"KINEMATIC ANALYSIS AND SIMULATION OF TWO-LEGGED THEO-JANSEN'S MECHANISM"** is a bonafide work carried out by **KILARAM JYOTSHNA(314126520080)**, **MADDU VIJUSHA(314126520090),SANAPALA SUNEETHA(314126520142), N.DINESH SRINIVASA RAO(314126520105), S.SHREEJI(314126520143)** during the year 2017-2018 under the guidance of **Sri. R. CHANDRAMOULI,** in partial fulfillment of requirements for the award of the degree of Mechanical Engineering In Department of Mechanical Engineering, Anil Neerukonda Institute of Technology And Sciences, Affliated To Andhra University, Visakhapatnam.

APPROVED BY

24.4.18

(DR.B. NAGARAJU)
Head of the Department
Dept of Mechanical Engineering
ANITS, Sangivalsa
Visakhapatnam

PROFESSOR & HEAD
Department of Mechanical Engineering
ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY & SCIENCES
Sangivalasa 531 162 VISAKHAPATNAM Dist A P

PROJECT GUIDE

R. Chandramouli

(Sri.R.CHANDRAMOULI)
Associate professor
Dept of Mechanical Engineering
ANITS, Sangivalsa
Visakhapatnam

THIS PROJECT IS APPROVED BY THE BOARD OF EXAMINERS

INTERNAL EXAMINER:

Dr. B. Naga Raju
M.Tech,M.E.,Ph.d
Professor & HOD
Dept.of Mechanical Engineering
ANITS, Sangivalasa,
Visakhapatnam-531 162.

EXTERNAL EXAMINER:

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K. JYOTSHNA (314126520080)
M.VIJUSHA (314126520090)
S.SUNEETHA (314126520142)
N.DINESH SRINIVASA RAO (314126520105)
S.SHREEJI (314126520143)

ABSTRACT

Theo Jansen mechanism is gaining wide spread popularity among researchers on legged robotics due to its scalable design, energy efficiency and deterministic foot trajectory. Presently research is being conducted on Jansen's linkage as it gives an alternative to using wheels in uneven surfaces. Many researchers have done analysis on this mechanism using many methods, but in this work complex algebraic method is used, which is easy to understand and for the scope of easy manipulation. The use of complex numbers makes it possible to consider not only angles and distances, as rotations of cranks or translations of sliders, but also vectors, to express analytically the arbitrary motions of points in a plane. Hence in the present work kinematic analysis (i.e position, angular velocity and angular acceleration of every link) of the two legged planar Jansen mechanism is performed using complex Algebraic method and further MATLAB CODE is developed for simulation of the mechanism.

The angular displacement, angular velocity and angular acceleration are evaluated for all the links of the mechanism for one complete cycle of input link. The veracity of the method is verified by graphical approach.

CONTENTS

NOMENCLATURE

For left & right leg:

a = length of link1 (m)

b = length of link2 (m)

c = length of link3 (m)

d = length of link4 (m)

e = length of link5 (m)

f = length of link6 (m)

g = length of link7 (m)

h = length of link10 (m)

i = length of link11 (m)

j = length of link12 (m)

k = length of link8 (m)

l = length of link9 (m)

θ_i = Angular position of link 'i' with respect to x-axis (degrees)

ω_i = Angular velocity of link 'i' (rad/s)

α_i = Angular acceleration of link 'i' (rad/s^2)

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CHAPTER 1

1. INTRODUCTION

1.1 Introduction to Theo-Jansen's mechanism

The Jansen mechanism is a one degree-of-freedom, planar, 8-link, leg mechanism designed by the Dutch kinetic sculptor Theo Jansen to simulate a smooth walking motion. It was created during his works of fusion of art and engineering, and the history of the linkage development and invention is described in his study [1]. This linkage, depicted in Figure 1, has three independent loops and consists of six binary links, one ternary link, and a coupler link with seven revolute joints. Out of seven revolute joints four are binary type and three ternary type joints. Jansen's linkage bears artistic as well as mechanical merit for its simulation of organic walking motion using a simple rotary input. Jansen has used his mechanism in a variety of kinetic sculptures which are known as Strandbeests [2]. It can be used in mobile robotic applications and in gait analysis. Shunsuke Nansai et al., [3] presented dynamic analysis of a four legged Theo Jansen link mechanism using projection method that results in constraint force and equivalent Lagrange's equation of motion necessary for any meaningful extension and/or optimization of this niche mechanism. Numerical simulations using MaTX is presented in conjunction with the dynamic analysis. This research sets a theoretical basis for future investigation into Theo Jansen mechanism. A. Aan and M. Heinloo [4] presented the results of kinematic and dynamic calculations of Theo Jansen's walking linkage on the worksheet of Mathcad. To validate the kinematic calculations, a video clip with simulation of the motion of Theo Jansen's mechanism is composed. The synthesis of a flywheel for Theo Jansen's linkage input link to decrease the fluctuation in its rotation is considered in detail.

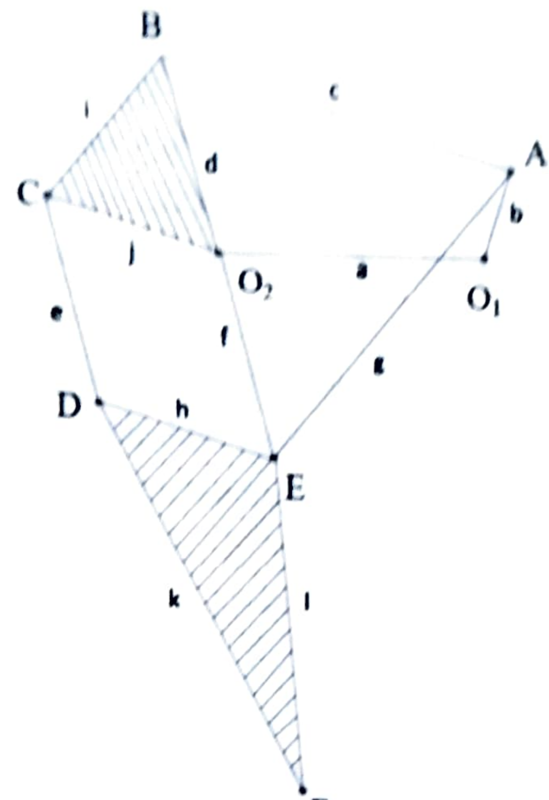


Figure-1.1: Theo-Jansen's Linkage

Theo Jansen mechanism is gaining wide spread popularity among legged robotics researchers due to its scalable design, energy efficiency, bio-inspired locomotion, deterministic foot trajectory. Based on the literatures reviewed it has been observed that presently research is being conducted on Jansen's linkage as it gives an alternative to using wheels in uneven surfaces. Very few works have been done on Kinematic and Dynamic analysis of Jansen's linkage. Although researchers [3-10] have done analysis on jansen's mechanism, they have used matrix method, bond graph approach, projection method etc. Many researchers [11-15] have applied algebraic approach to analyze different mechanisms.

Hence an attempt is made in this work to do the kinematic analysis of two legged Jansen's mechanism using complex algebraic approach [16], which is easy to understand and for the scope of easy manipulation. The use of complex numbers makes it possible to consider not only angles and distances, as rotations of cranks or translations of sliders, but also vectors, to express analytically the arbitrary motions of points in a plane [17]. The kinematic analysis determines the trajectories of various points on the mechanism including the foot point trajectory in the chassis reference frame. It is advantageous that the leg system maximize the amount of time that a foot spends in contact with the ground (step length) to increase stability throughout the gait [10]. In order to be energy efficient, the walker must maximize the distance moved per unit of energy lost. Increasing the stride/step length will help accomplish this because each locomotive cycle will result in more forward movement. The step height should be high enough to step over minor inconsistencies in the terrain in order to prevent foot dragging.

Thus the variation in step length and step height with change in stationary link length and crank radius is also evaluated and presented in this work. The simulation of the above mechanism is also carried out by writing a MATLAB code.

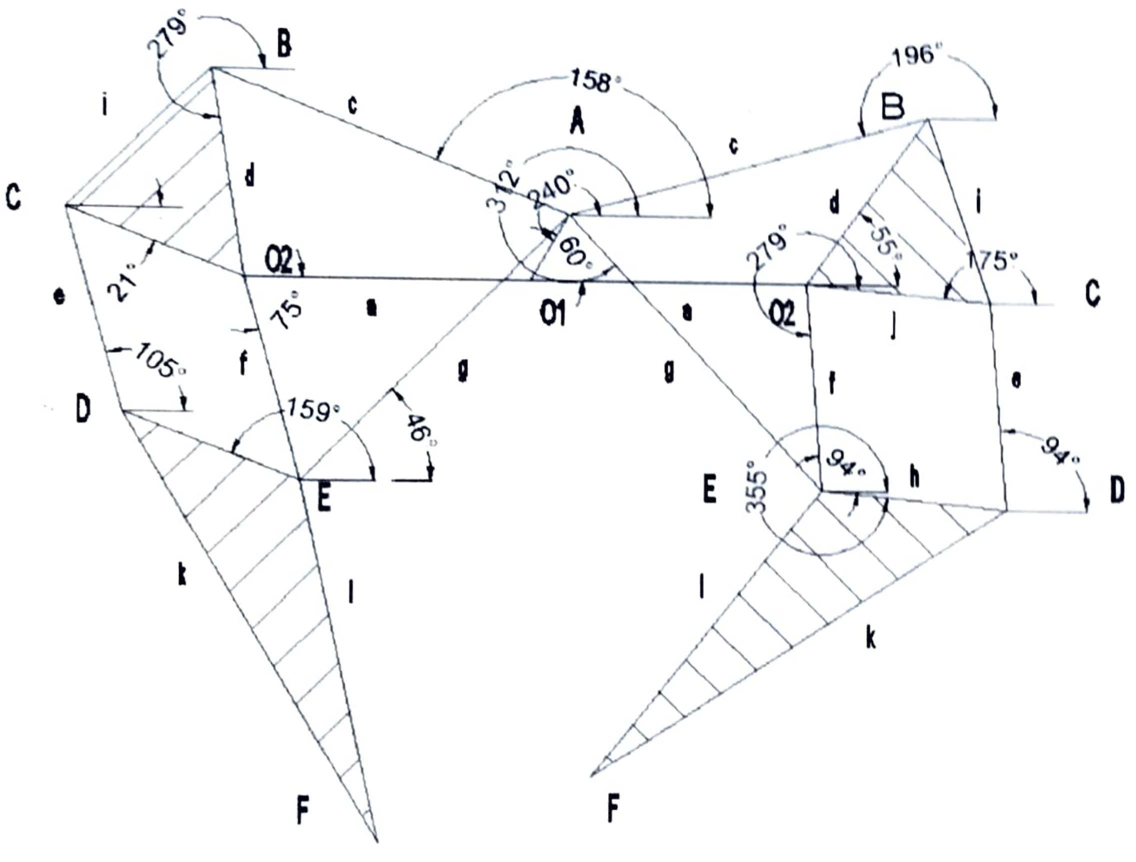


Figure-1.2: Angular position of links for a crank angle of 60° for two-legged Theo-Jansen's mechanism.

Table-1.1

Link lengths in Jansen's leg mechanism [18]

Link	Link length (m)	Link Length in proportion to crank length
Link- a	0.15	3.5971
Link- b (CRANK)	0.0417	1.00
Link- c	0.2033	4.8752
Link- d	0.1141	2.7362
Link- e	0.1141	2.7362
Link- f	0.1141	2.7362
Link- g	0.2033	4.8752
Link- h	0.0997	2.3908
Link- i	0.1077	2.5827
Link- j	0.10	2.3980
Link- k	0.268	6.4268
Link- l	0.20	4.7961

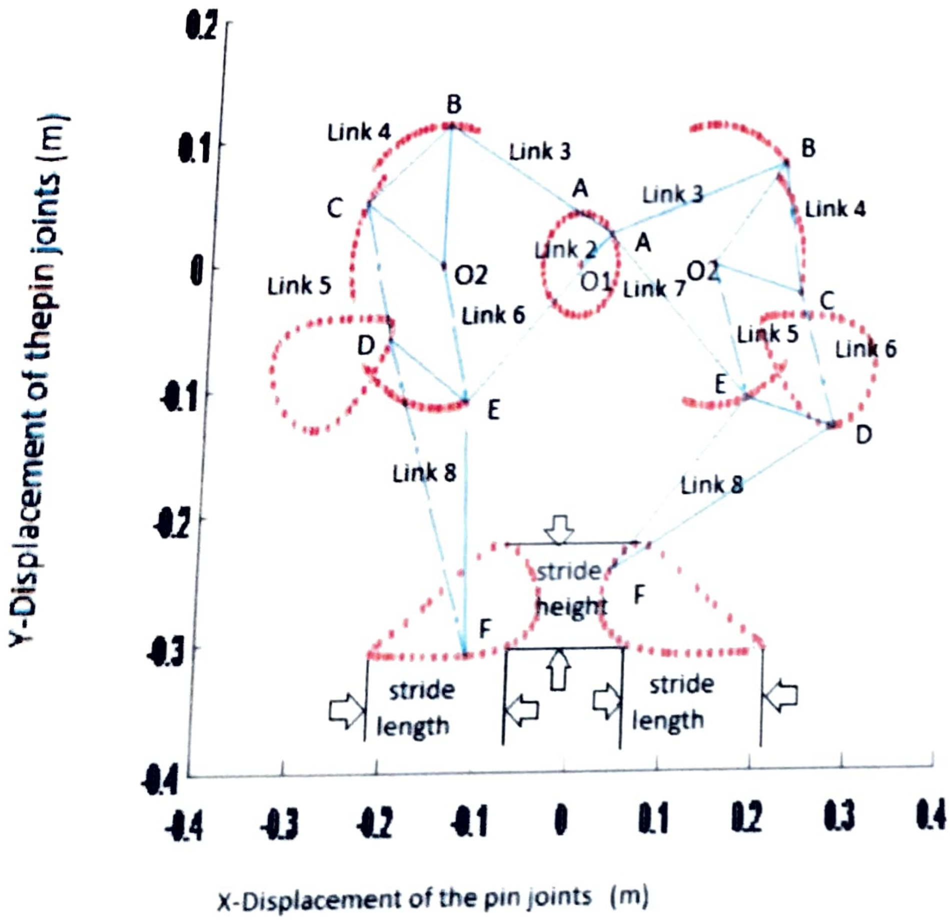


Figure-1.3: Notations of two legged Theo-Jansen's mechanism

To design the legged walking mechanism, shown in figure 1.3, O_1A serves as an input link and DEF serves as the foot-link with F as the tracer point in both the legs. In our design, link O_1O_2 is fixed. The Mechanism is designed such that the trajectory of the tracer point is an ovoid, as shown in figure 1.3, for two reasons: (1) the ovoid path enables the walking mechanism to step over small obstacles without significantly raising its body or applying an additional DOF motion and, (2) it can also minimize the slamming effect caused by the inertia forces during walking. The path of the tracer point is composed of two portions during each step. The first portion is the propelling portion, between $F_1$and F_2. Where the tracer point, F is in contact with the ground. The second portion is the returning portion, where the tracer point F is not in contact with the ground. The distance between F_1 and F_2 is the stride length, which is proportional to the step length, and the height H is the maximum height of an obstacle that the walking machine can step over. Not that the stride length F_1F_2 is different from the step length in that during the design, the "Hip" is fixed and the stride length is propelling distance of the "Hip" in actual walking, while the step length is the distance between two subsequent contact points of foot, and the ground. However, the stride length and the step length are linear proportional, i.e., a longer stride length leads to a longer step length.

1.2 Degrees of freedom for two legged Theo-Jansen's mechanism:

F=3(n-1)-2j-h

Where n=number of links,

j= number of binary joints

h=number of higher pairs

F=3(14-1)-2*19-0

F= 1

CHAPTER 2

2. INTRODUCTION TO MATLAB

2.1 What is MATLAB?

MATLAB is widely used in all areas of applied mathematics, in education and research at universities, and in the industry. MATLAB stands for MATrixLABoratory and the software is built up around vectors and matrices. This makes the software particularly useful for linear algebra but MATLAB is also a great tool for solving algebraic and differential equations and for numerical integration. MATLAB has powerful graphic tools and can produce nice pictures in both 2D and 3D. It is also a programming language, and is one of the easiest programming languages for writing mathematical programs. MATLAB also has some tool boxes useful for signal processing, image processing, optimization, etc.

Table 2.1: MATLAB commands

Operation, function or constant	**MATLAB command**
+ (addition)	`+`
- (subtraction)	`-`
� (multiplication)	`*`
/ (division)	`/`
|x| (absolute value of x)	`abs(x)`
square root of x	`sqrt(x)`
e^x	`exp(x)`
ln x (natural log)	`log(x)`
$\log_{10}$ x (base 10 log)	`log10(x)`
sin x	`sind(x)`
cos x	`cosd(x)`
tan x	`tand(x)`
cot x	`cotd(x)`
arcsin x	`asind(x)`
arccos x	`acosd(x)`
arctan x	`atand(x)`
arccot x	`acot(x)`
n! (n factorial)	`gamma(n+1)`

e (2.71828...)	exp(1)
π (3.14159265...)	Pi
Label the horizontal axis.	xlabel('text')
Label the vertical axis.	ylabel('text')
Attach a title to the plot.	title('text')
Change the limits on the x and y axis.	axis([xminxmaxyminymax])
"Keep plotting in the same window."	hold on
Turn off the "keep-plotting-in-the-same-window-command".	hold off

2.2 The MATLAB environment

The MATLAB environment (on most computer systems) consists of menus, buttons and a writing area similar to an ordinary word processor. There are plenty of help functions that you are encouraged to use. The writing area that you will see when you start MATLAB is called the *command window*. In this window you give the commands to MATLAB. For example, when you want to run a program you have written for MATLAB you start the program in the command window by typing its name at the prompt. The command window is also useful if you just want to use MATLAB as a scientific calculator or as a graphing tool. If you write longer programs, you will find it more convenient to write the program code in a separate window, and then run it in the command window.

2.3 Vectors and matrices in MATLAB

Matrices can be created according to the following example.

The matrix A= $\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix}$ is created by typing`A= [1 2 3; 4 5 6; 7 8 9],`

Rows are separated with semi-colons,

2.4 How to plot with MATLAB

There are different ways of plotting in MATLAB. The following two techniques, illustrated by examples, are probably the most useful ones.

Example *1:* Plot sin(x^2) on the interval [-5,5]. To do this, type the following:

```
x=-5:0.01:5;

y=sin(x.^2);

plot(x,y)
```

Example *2:* Plot exp(sin(x)) on the interval [-□,□]. To do this, type the following:

```
x=linspace(-pi,pi,101);

y=exp(sin(x));

plot(x,y)
```

CHAPTER 3

3. LITERATURE REVIEW

3.1 Literature review:

[1] Jansen T. The great pretender. Rotterdam: 010 Publishers, 2007
Dutch kinetic sculptor Theo Jansen to simulate a smooth walking motion created this mechanism during his works of fusion of art and engineering, and the history of the linkage development and invention is described in his study.

[2] T. Jansen, Strandbeest, Website, 2014. http://www.strandbeest.com/>.
Jansen has used his mechanism in a variety of kinetic sculptures which are known as Strandbeests.

[3] ShunsukeNansai, Mohan Rajesh Elara, and Masami Iwase. Dynamic analysis and modeling of Jansen mechanism.Procedia Engineering, 2013, 64;1562-71
He presented dynamic analysis of a four legged Theo Jansen link mechanism using projection method that results in constraint force and equivalent Lagrange's equation of motion necessary for any meaningful extension and/or optimization of this niche mechanism. Numerical simulations using MaTX is presented in conjunction with the dynamic analysis. This research sets a theoretical basis for future investigation into Theo Jansen mechanism.

[4] A. Aan and M. Heinloo . Analysis and Synthesis of the Walking Linkage of Theo jansen with a flywheel-Agronomy Research, 2014, 12(2), 657–662.
They presented the results of kinematic and dynamic calculations of Theo Jansen's walking linkage on the worksheet of Mathcad. To validate the kinematic calculations, a video clip with simulation of the motion of Theo Jansen's mechanism is composed. The synthesis of a flywheel for Theo Jansen's linkage input link to decrease the fluctuation in its rotation is considered in detail.

[5] LalitPatnaik&LoganathanUmanand. Kinematics and dynamics of Jansen leg mechanism: A bond graph approach. Simulation modelling practice and theory(Elsevier), 2016, 60, 160-169.

Here, the forward kinematics, accomplished using circle intersection method, determines the trajectories of various points on the mechanism in the chassis (stationary link) reference frame. From the foot point trajectory, the step length is shown to vary linearly while step height varies non-linearly with change in crank radius. A dynamic model for the Jansen leg mechanism is proposed using bond graph approach with modulated multiport transformers.

[6] Dileepkumar P, KINEMATIC AND DYNAMIC ANALYSIS OF JANSEN'S 8 LINK MECHANISM BY COMPLEX ALGEBRA" M.Tech project-2017, ANITS.
He has done kinematic and dynamic analysis of Jansen's mechanism (Left leg) by complex algebraic method.

3.2 Scope of the Present Work:

Based on the literatures reviewed, it has been observed that previous works on Jansen's mechanism were being carried out using matrix method and bond graph approach. The algebraic method has its advantages over other methods for kinematic analysis; the use of Complex Algebra makes it possible to consider not only angles and distances, as rotations of cranks or translations of sliders, but also vectors, to express analytically the arbitrary motions of points in a plane. Thus in our present work Algebraic method is being used to do kinematic analysis of Two-legged Theo-Jansen's mechanism and further code is developed to perform simulation of the mechanism.

CHAPTER 4

4. KINEMATIC ANALYSIS OF LEFT LEG

Here the complex Algebra is used for vectors to develop and derive the equations for angular positions of linkages. From figure (4.1) each loop has been analysed as follows.

4.1 POSITION ANALYSIS OF LEFT LEG :

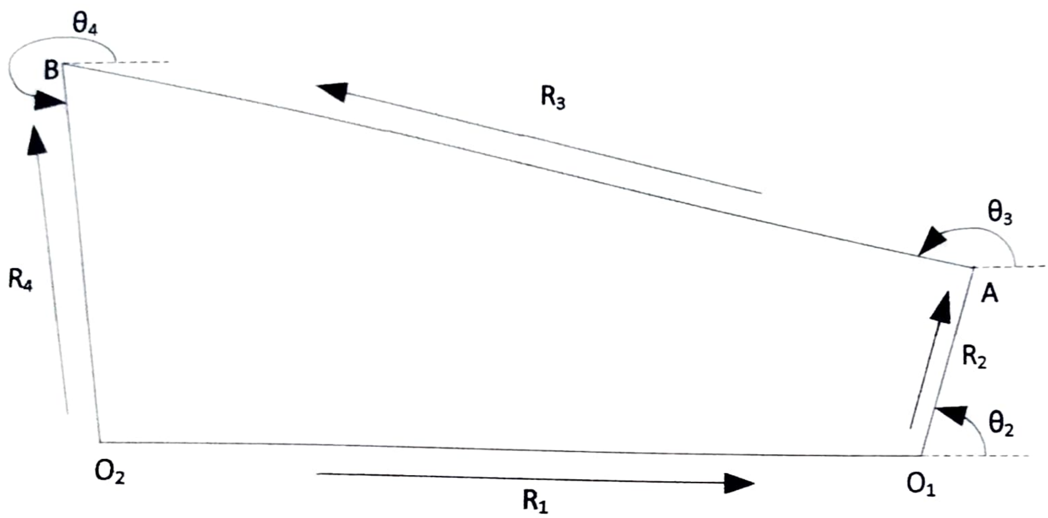


Figure 4.1 The vector loopO_1ABO_2

4.1.1 The vector loop of O_1ABO_2 is $R_1+R_2+R_3+R_4=0$

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as $O_1O_2 = a, O_1A = b, AB = c, BO_2 = d$ as shown in figure (4.1).

$$ae^{i\theta_1} + be^{i\theta_2} + ce^{i\theta_3} + de^{i\theta_4} = 0 \qquad \text{......... (4.1)}$$

Separating the real and imaginary parts in eq (4.1), the real part is

$$a\cos\theta_1 + b\cos\theta_2 + c\cos\theta_3 + d\cos\theta_4 = 0 \qquad \text{.......... (4.2)}$$

The imaginary part is

$$a\sin\theta_1 + b\sin\theta_2 + c\sin\theta_3 + d\sin\theta_4 = 0 \qquad \text{............ (4.3)}$$

But the angle made by the fixed link is 0°, therefore by substituting $\theta_1 = 0^0$

in eq (4.2) and (4.3) we get,

$$a + b\cos\theta_2 + c\cos\theta_3 + d\cos\theta_4 = 0 \qquad \ldots\ldots\ldots (4.4)$$

$$b\sin\theta_2 + c\sin\theta_3 + d\sin\theta_4 = 0 \qquad \ldots\ldots\ldots (4.5)$$

eliminating $\rightarrow \theta_4$ From the above equations (4.4) & (4.5) we get

$$-d\cos\theta_4 = a + b\cos\theta_2 + c\cos\theta_3 \qquad \ldots\ldots\ldots (4.6)$$

$$-d\sin\theta_4 = b\sin\theta_2 + c\sin\theta_3 \qquad \ldots\ldots\ldots (4.7)$$

Squaring and adding the above equations (4.6) & (4.7)

$$d^2 = a^2 + b^2 + c^2 + 2ab\cos\theta_2 + 2bc\cos\theta_2\cos\theta_3 + 2ac\cos\theta_3 + 2bc\sin\theta_2\sin\theta_3$$

$$\frac{d^2 - a^2 - b^2 - c^2}{2bc} = \frac{a}{c}\cos\theta_2 + \cos\theta_2\cos\theta_3 + \frac{a}{b}\cos\theta_3 + \sin\theta_2\sin\theta_3 \qquad \ldots\ldots\ldots (4.8)$$

Let $k_1 = \frac{a}{c}, k_2 = \frac{a}{b}, k_3 = \frac{d^2 - a^2 - b^2 - c^2}{2bc}$

Substituting $\mathbf{k_1,k_2,k_3}$ in eq (4.8) we get

$$k_3 = k_1\cos\theta_2 + k_2\cos\theta_3 + (\cos\theta_2\cos\theta_3 + \sin\theta_2\sin\theta_3) \qquad \ldots\ldots\ldots (4.9)$$

By substituting $\cos\theta_3 = \frac{1-\tan^2\left(\frac{\theta_3}{2}\right)}{1+\tan^2\left(\frac{\theta_3}{2}\right)}, \sin\theta_3 = \frac{2\tan\left(\frac{\theta_3}{2}\right)}{1+\tan^2\left(\frac{\theta_3}{2}\right)}$ in eq (4.9)

$$A\tan^2\left(\frac{\theta_3}{2}\right) + B\tan\left(\frac{\theta_3}{2}\right) + C = 0 \qquad \ldots\ldots\ldots (4.10)$$

By solving the above quadratic equation (4.10) we get

$$\theta_3 = 2\tan^{-1}\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right) \qquad \ldots\ldots\ldots (4.11)$$

Similarly for θ_4, we get

$$\theta_4 = 2\tan^{-1}\left(\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right) \qquad \text{.......... (4.12)}$$

4.1.2 The vector loop of $ABO_2E$is $R_3+R_4+R_6+R_7=0$

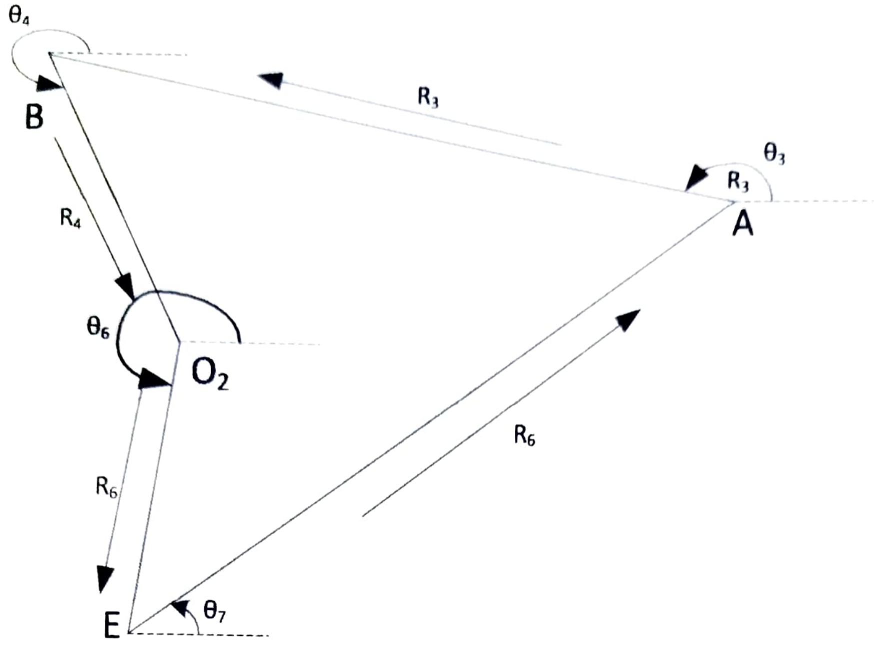


Figure 4.2 The vector loopABO_2E

The vector loop $ABO_2E$is $R_3+R_4+R_6+R_7=0$

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as $O_2E = f, AE = g, AB = c, BO_2 = d$ as shown in figure,

$$ce^{i\theta_3} + de^{i\theta_4} + fe^{i\theta_6} + ge^{i\theta_7} = 0 \qquad \text{.......... (4.13)}$$

Separating the real and imaginary parts in eq (4.13), the real part is

$$c\cos\theta_3 + d\cos\theta_4 + f\cos\theta_6 + g\cos\theta_7 = 0 \qquad \text{.......... (4.14)}$$

The imaginary part is

$$c\sin\theta_3 + d\sin\theta_4 + f\sin\theta_6 + g\sin\theta_7 = 0 \qquad \text{.......... (4.15)}$$

$$M_1 = c\cos\theta_3 + d\cos\theta_4$$

$$M_2 = c\sin\theta_3 + d\sin\theta_4$$

$$M_1 + f\cos\theta_6 + g\cos\theta_7 = 0 \qquad \text{.......... (4.16)}$$

$$M_2 + f\sin\theta_6 + g\sin\theta_7 = 0 \qquad \text{.......... (4.17)}$$

eliminating $\rightarrow \theta_7$ From the above equations (4.16) & (4.17) we get

$$-g\cos\theta_7 = M_1 + f\cos\theta_6 \qquad \text{.......... (4.18)}$$

$$-g\sin\theta_7 = M_2 + f\sin\theta_6 \qquad \text{.......... (4.19)}$$

Squaring and adding the above equations (4.18) & (4.19)

$$g^2 = M_1^2 + M_2^2 + f^2 + 2f(M_1\cos\theta_6 + M_2\sin\theta_6)$$

$$M_1\cos\theta_6 + M_2\sin\theta_6 = \frac{g^2 - M_1^2 - M_2^2 - f^2}{2f}$$

$$P_1 = \frac{g^2 - M_1^2 - M_2^2 - f^2}{2f}$$

$$P_1 = M_1\cos\theta_6 + M_2\sin\theta_6 \qquad \text{.......... (4.20)}$$

By substituting $\cos\theta_6 = \dfrac{1-\tan^2\left(\frac{\theta_6}{2}\right)}{1+\tan^2\left(\frac{\theta_6}{2}\right)}$, $\sin\theta_6 = \dfrac{2\tan\left(\frac{\theta_6}{2}\right)}{1+\tan^2\left(\frac{\theta_6}{2}\right)}$

We get, $G\tan^2\left(\frac{\theta_6}{2}\right) + H\tan\left(\frac{\theta_6}{2}\right) + I = 0$ .... (4.21)

$$G = P_1 + M_1$$

$$H = -2M_2$$

$$I = P_1 - M_1$$

By solving the above quadratic equation (4.21), we get

$$\theta_6 = 2\tan^{-1}\left(\frac{-H \pm \sqrt{H^2 - 4IG}}{2G}\right) \qquad \text{.......... (4.22)}$$

Similarly for θ_7, we get

$$\theta_7 = 2\tan^{-1}\left(\frac{-K \pm \sqrt{K^2 - 4JL}}{2J}\right) \qquad \text{.......... (4.23)}$$

4.1.3 The vector loop $EDCO_2$ is $R_6+R_5+R_4+R_6=0$

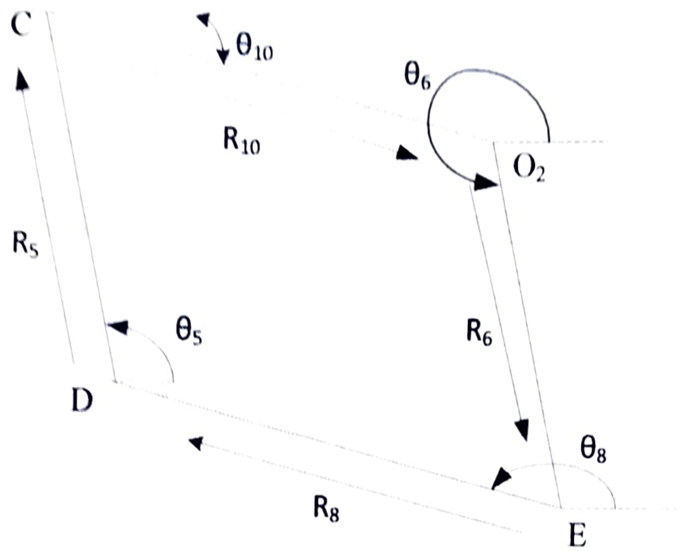


Figure 4.3 The vector loop$EDCO_2$

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as $O_2E = f, CD = e, DE = h, O_2C = j$ as shown in figure

$$fe^{i\theta_6} + je^{i\theta_{10}} + ee^{i\theta_5} + he^{i\theta_8} = 0 \qquad \text{.......... (4.24)}$$

Separating the real and imaginary parts in eq (4.13), The real part is

$$f\cos\theta_6 + j\cos\theta_{10} + e\cos\theta_5 + h\cos\theta_8 = 0 \qquad \text{.......... (4.25)}$$

The imaginary part is

$$f\sin\theta_6 + j\sin\theta_{10} + e\sin\theta_5 + h\sin\theta_8 = 0 \qquad \text{........... (4.26)}$$

$$N_1 = f\cos\theta_6 + j\cos\theta_{10}$$

$$N_2 = f\sin\theta_6 + j\sin\theta_{10}$$

Where, $\theta_{10} = 60+\theta_4$

$$N_1 + e\cos\theta_5 + h\cos\theta_8 = 0 \qquad \text{..........} (4.27)$$

$$N_2 + e\sin\theta_5 + h\sin\theta_8 = 0 \qquad \text{..........} (4.28)$$

$\text{eliminating} \rightarrow \theta_5$

From the above equations (4.27) & (4.28) we get

$$-e\cos\theta_5 = N_1 + h\cos\theta_8 \qquad \text{..........} (4.29)$$

$$-e\sin\theta_5 = N_2 + h\sin\theta_8 \qquad \text{..........} (4.30)$$

Squaring and adding the above equations (4.29) & (4.30)

$$e^2 = N_1^2 + N_2^2 + h^2 + 2h(N_1\cos\theta_8 + N_2\sin\theta_8)$$

$$N_1\cos\theta_8 + N_2\sin\theta_8 = \frac{e^2 - N_1^2 - N_2^2 - h^2}{2h}$$

$$q_1 = \frac{e^2 - N_1^2 - N_2^2 - h^2}{2h}$$

$$q_1 = N_1\cos\theta_8 + N_2\sin\theta_8 \qquad \text{..........} (4.31)$$

By substituting $\cos\theta_8 = \dfrac{1-\tan^2\left(\dfrac{\theta_8}{2}\right)}{1+\tan^2\left(\dfrac{\theta_8}{2}\right)}$, $\sin\theta_8 = \dfrac{2\tan\left(\dfrac{\theta_8}{2}\right)}{1+\tan^2\left(\dfrac{\theta_8}{2}\right)}$.

We get, $$J\tan^2\left(\frac{\theta_6}{2}\right) + K\tan\left(\frac{\theta_6}{2}\right) + L = 0 \qquad \text{..........} (4.32)$$

$$J = q_1 + N_1$$

$$K = -2N_2$$

$$L = q_1 - N_1$$

By solving the above quadratic equation (4.32), we get

$$\theta_8 = 2\tan^{-1}\left(\frac{-K \pm \sqrt{K^2 - 4JL}}{2J}\right) \qquad \text{..........(4.33)}$$

Similarly for θ_8, we get

$$\theta_5 = 2\tan^{-1}\left(\frac{-Y \pm \sqrt{Y^2 - 4XZ}}{2X}\right) \qquad \text{..........(4.34)}$$

4.2 VELOCITY ANALYSIS OF LEFT LEG:

4.2.1 Velocity of the vector loop of O_1ABO_2

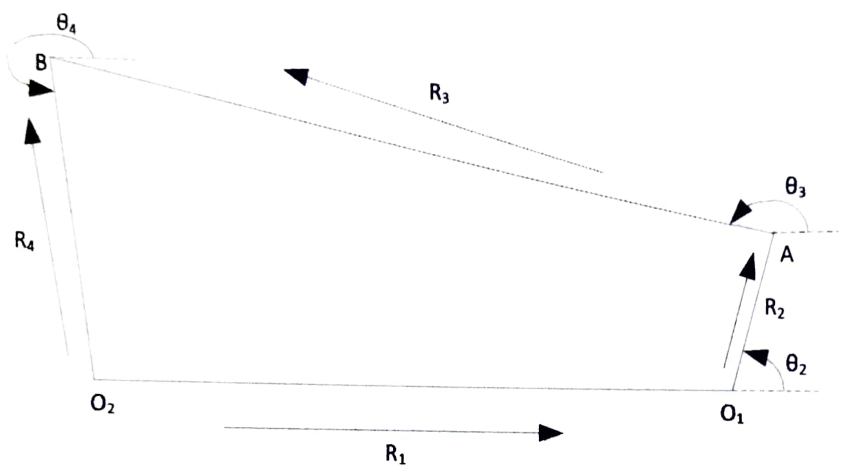


Figure 4.4 The vector loopO_1ABO_2

Differentiating position equation (4.1) of first loop to get the velocity expression

$$b\omega_2 ie^{i\theta_2} + c\omega_3 ie^{i\theta_3} + d\omega_4 ie^{i\theta_4} = 0 \qquad \text{..........(4.35)}$$

Separating the real and imaginary parts in eq (4.35), The real part is

$$b\omega_2 \cos\theta_2 + c\omega_3 \cos\theta_3 + d\omega_4 \cos\theta_4 = 0 \qquad \text{..........(4.36)}$$

The imaginary part is

$$b\omega_2 \sin\theta_2 + c\omega_3 \sin\theta_3 + d\omega_4 \sin\theta_4 = 0 \qquad \text{..........(4.37)}$$

Multiplying eq (4.36) with $\sin\theta_4$ and eq (4.37) with $\cos\theta_4$ we get,

$$b\omega_2 \sin\theta_2 \cos\theta_4 + c\omega_3 \sin\theta_3 \cos\theta_4 + d\omega_4 \sin\theta_4 \cos\theta_4 = 0 \qquad \text{..........(4.38)}$$

$$b\omega_2 \cos\theta_2 \sin\theta_4 + c\omega_3 \cos\theta_3 \sin\theta_4 + d\omega_4 \cos\theta_4 \sin\theta_4 = 0 \qquad \ldots\ldots\ldots\ldots (4.39)$$

Subtracting the above equations, we get

$$b\omega_2 (\sin\theta_2 \cos\theta_4 - \cos\theta_2 \sin\theta_4) + c\omega_3 (\sin\theta_3 \cos\theta_4 - \cos\theta_3 \sin\theta_4) = 0 \qquad \ldots\ldots (4.40)$$

$$b\omega_2 (\sin(\theta_2 - \theta_4)) + c\omega_3 (\sin(\theta_3 - \theta_4)) = 0$$

By solving above equation (4.40), we get

$$\omega_3 = \frac{b\omega_2 (\sin(\theta_2 - \theta_4))}{c(\sin(\theta_4 - \theta_3))} \qquad \ldots\ldots\ldots\ldots (4.41)$$

Similarly for ω_4,

$$\omega_4 = \frac{b\omega_2 (\sin(\theta_2 - \theta_3))}{d(\sin(\theta_3 - \theta_4))} \qquad \ldots\ldots\ldots\ldots (4.42)$$

4.2.2 Velocity of vector loop equation for ABO_2E

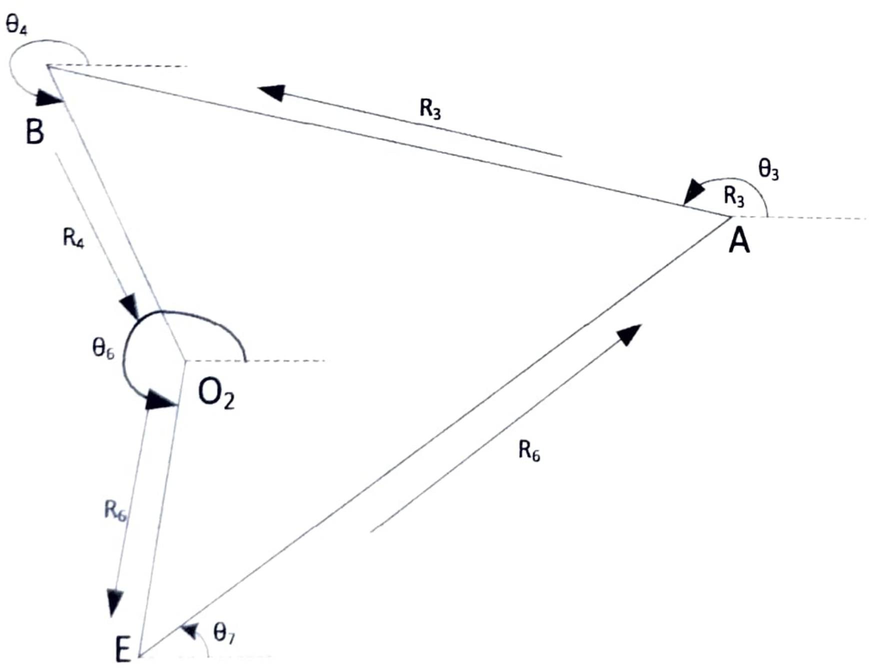


Figure 4.5 The vector loopABO_2E

Differentiating position equation (4.13) of second loop to get the velocity expression

$$c\omega_3 ie^{i\theta_3} + d\omega_4 ie^{i\theta_4} + f\omega_6 ie^{i\theta_6} + g\omega_7 ie^{i\theta_7} = 0 \qquad \text{..........} (4.43)$$

Separating the real and imaginary parts in eq (4.43), the real part is

$$c\omega_3 \cos\theta_3 + d\omega_4 \cos\theta_4 + f\omega_6 \cos\theta_6 + g\omega_7 \cos\theta_7 = 0 \qquad \text{..........} (4.44)$$

The imaginary part

$$c\omega_3 \sin\theta_3 + d\omega_4 \sin\theta_4 + f\omega_6 \sin\theta_6 + g\omega_7 \sin\theta_7 = 0 \qquad \text{..........} (4.45)$$

Multiplying eq (4.44) with $\sin\theta_7$ and eq (4.45) with $\cos\theta_7$ we get

$$c\omega_3 \sin\theta_3 \cos\theta_7 + d\omega_4 \sin\theta_4 \cos\theta_7 + f\omega_6 \sin\theta_6 \cos\theta_7 + g\omega_7 \sin\theta_7 \cos\theta_7 = 0 \quad \text{.....} (4.46)$$

$$c\omega_3 \cos\theta_3 \sin\theta_7 + d\omega_4 \cos\theta_4 \sin\theta_7 + f\omega_6 \cos\theta_6 \sin\theta_7 + g\omega_7 \cos\theta_7 \sin\theta_7 = 0 \quad \text{....} (4.47)$$

Subtracting the above equations, we get

$$c\omega_3 (\sin\theta_3 \cos\theta_7 - \cos\theta_3 \sin\theta_7) + d\omega_4 (\sin\theta_4 \cos\theta_7 - \cos\theta_4 \sin\theta_7)$$
$$+ f\omega_6 (\sin\theta_6 \cos\theta_7 - \cos\theta_6 \sin\theta_7) + g\omega_7 (\sin\theta_7 \cos\theta_7 - \cos\theta_7 \sin\theta_7) = 0 \quad \text{...} (4.48)$$
$$c\omega_3 \sin(\theta_3 - \theta_7) + d\omega_4 \sin(\theta_4 - \theta_7) + f\omega_6 \sin(\theta_6 - \theta_7)$$

By solving above equation (4.48), we get

$$\omega_6 = \frac{c\omega_3 \sin(\theta_3 - \theta_7) + d\omega_4 \sin(\theta_4 - \theta_7)}{f * \sin(\theta_7 - \theta_6)} \qquad \text{..........} (4.49)$$

Similarly for ω_7,

$$\omega_7 = \frac{c\omega_3 \sin(\theta_3 - \theta_6) + d\omega_4 \sin(\theta_4 - \theta_6)}{f * \sin(\theta_6 - \theta_7)}. \qquad \text{..........} (4.50)$$

4.2.3 Velocity of vector loop equation for $EDCO_2$

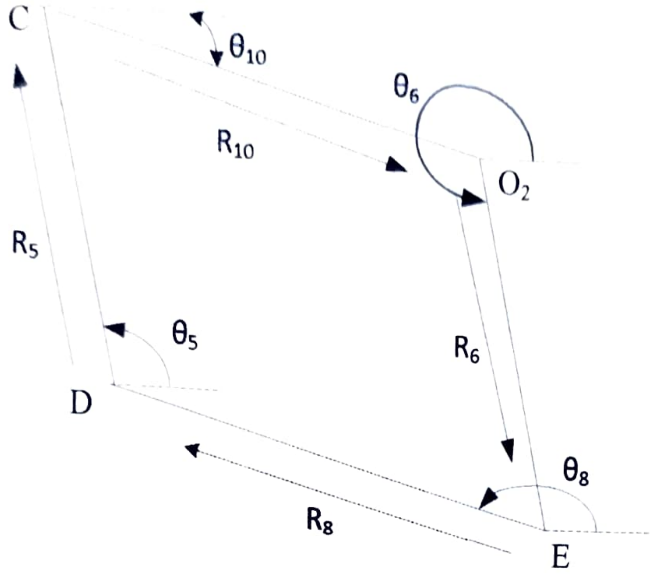


Figure 4.6 The vector loop$EDCO_2$

Differentiating position equation (4.24) of third loop to get the velocity expression

$$e\omega_5 ie^{i\theta_5} + f\omega_6 ie^{i\theta_6} + h\omega_8 ie^{i\theta_8} + j\omega_{10} ie^{i\theta_{10}} = 0. \quad \text{..........} (4.51)$$

Separating the real and imaginary parts in eq (4.51), the real part is

$$e\omega_5 \cos\theta_5 + f\omega_6 \cos\theta_6 + h\omega_8 \cos\theta_8 + j\omega_{10} \cos\theta_{10} = 0. \quad \text{..........} (4.52)$$

The imaginary part

$$e\omega_5 \sin\theta_5 + f\omega_6 \sin\theta_6 + h\omega_8 \sin\theta_8 + j\omega_{10} \sin\theta_{10} = 0 \quad \text{...........} (4.53)$$

Multiplying eq (4.52) with $\sin\theta_8$ and eq (4.53) with $\cos\theta_8$ we get

$$e\omega_5 \sin\theta_5 \cos\theta_8 + f\omega_6 \sin\theta_6 \cos\theta_8 + h\omega_8 \sin\theta_8 \cos\theta_8 + j\omega_{10} \sin\theta_{10} \cos\theta_8 = 0 \text{....}(4.54)$$

$$e\omega_5 \cos\theta_5 \sin\theta_8 + f\omega_6 \cos\theta_6 \sin\theta_8 + h\omega_8 \cos\theta_8 \sin\theta_8 + j\omega_{10} \cos\theta_{10} \sin\theta_8 = 0 \text{.....}(4.55)$$

Subtracting the above equations, we get

$$e\omega_5 \sin\theta_5 \cos\theta_8 - \cos\theta_5 \sin\theta_8 + f\omega_6 \sin\theta_6 \cos\theta_8 - \cos\theta_6 \sin\theta_8$$
$$+h\omega_8 \sin\theta_8 \cos\theta_8 - \cos\theta_8 \sin\theta_8 + j\omega_{10} \sin\theta_{10} \cos\theta_8 - \cos\theta_{10} \sin\theta_8 = 0 \quad \text{........}(4.56)$$

$$e\omega_5 \sin(\theta_5 - \theta_8) + f\omega_6 \sin(\theta_6 - \theta_8) + j\omega_{10} \sin(\theta_{10} - \theta_8) = 0$$

By solving above equation (4.56), we get

$$\omega_5 = \frac{f\omega_6 \sin(\theta_6 - \theta_8) + j\omega_{10} \sin(\theta_{10} - \theta_8)}{e * \sin(\theta_8 - \theta_5)} \quad \text{.........(4.57)}$$

Similarly for ω_8,

$$\omega_8 = \frac{f\omega_6 \sin(\theta_6 - \theta_5) + j\omega_{10} \sin(\theta_{10} - \theta_5)}{h * \sin(\theta_5 - \theta_8)} \quad \text{.........(4.58)}$$

4.3 ACCELERATION ANALYSIS OF LEFT LEG:

4.3.1 Acceleration of vector loop equation for loop O_1ABO_2:

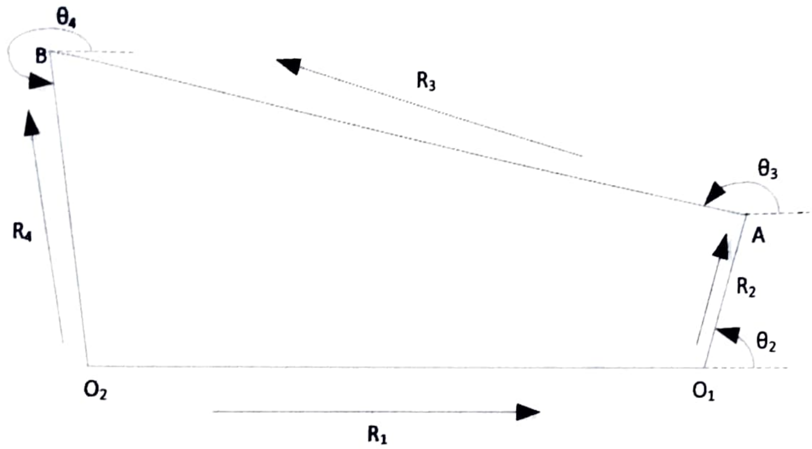


Figure 4.7 The vector loopO_1ABO_2

Differentiating the angular velocity equation (4.35) of first loop,

$$be^{i\theta_2}(i\alpha_2 - \omega_2^2) + ce^{i\theta_3}(i\alpha_3 - \omega_3^2) + de^{i\theta_4}(i\alpha_4 - \omega_4^2) = 0 \quad \text{..........(4.59)}$$

$$e^{i\theta_2} = \cos\theta_2 + i\sin\theta_2$$

$$e^{i\theta_3} = \cos\theta_3 + i\sin\theta_3$$

$$e^{i\theta_4} = \cos\theta_4 + i\sin\theta_4$$

Separating the real and imaginary parts of eq (4.59), we get real part,

$$b(\omega_2^2\cos\theta_2 + \alpha_2\sin\theta_2) + c(\omega_3^2\cos\theta_3 + \alpha_3\sin\theta_3) + d(\omega_4^2\cos\theta_4 + \alpha_4\sin\theta_4) = 0 \text{ ...(4.60)}$$

$$Y_2 = b\omega_2^2\cos\theta_2 + b\alpha_2\sin\theta_2 + c\omega_3^2\cos\theta_3 + d\omega_4^2\cos\theta_4$$

$$Y_2 + c\alpha_3\sin\theta_3 + d\alpha_4\sin\theta_4 = 0$$

Imaginary part

$$Y_1 = b\alpha_2\cos\theta_2 - b\omega_2^2\sin\theta_2 - c\omega_3^2\sin\theta_3 - d\omega_4^2\sin\theta_4$$

$$Y_1 + c\alpha_3 \cos\theta_3 + d\alpha_4 \cos\theta_4 = 0$$

By solving the above equations we get,

$$Y_2 \cos\theta_4 - Y_1 \sin\theta_4 + c\alpha_3 \sin(\theta_3 - \theta_4) = 0 \qquad (4.61)$$

By solving above equation (4.61), we get

$$\alpha_3 = \frac{Y_2 \cos\theta_4 - Y_1 \sin\theta_4}{c\sin(\theta_4 - \theta_3)} \qquad (4.62)$$

Similarly for α_4,

$$\alpha_4 = \frac{Y_2 \cos\theta_3 - Y_1 \sin\theta_3}{d\sin(\theta_3 - \theta_4)} \qquad (4.63)$$

4.3.2 Acceleration of vector loop equation for loop ABO$_2$E:

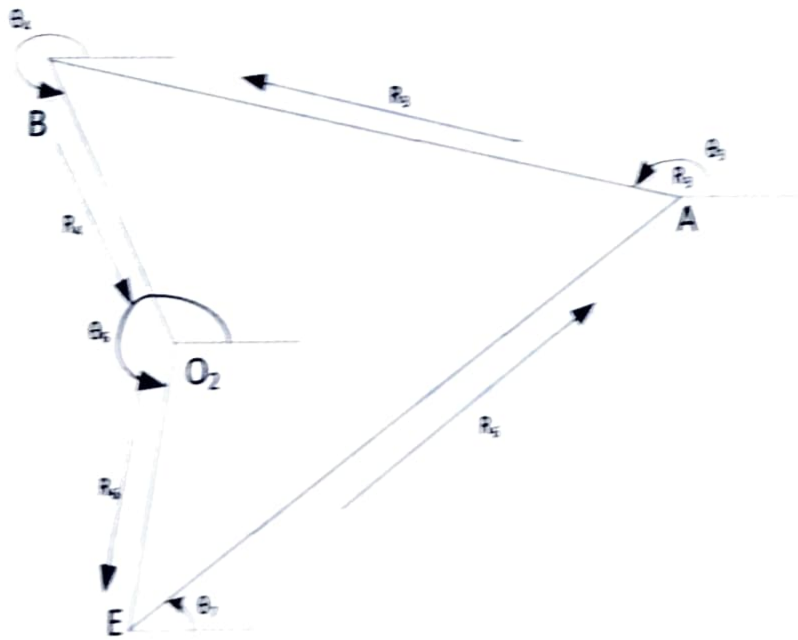


Figure 4.8 The vector loopABO$_2$E

Differentiating the angular velocity equation (4.43) of second loop

$$ce^{i\theta_3}(i\alpha_3 - \omega_3^2) + de^{i\theta_4}(i\alpha_4 - \omega_4^2) + fe^{i\theta_6}(i\alpha_6 - \omega_6^2) + fe^{i\theta_7}(i\alpha_7 - \omega_7^2) = 0 \qquad (4.64)$$

$$e^{i\theta_3} = \cos\theta_3 + i\sin\theta_3$$

$$e^{i\theta_4} = \cos\theta_4 + i\sin\theta_4$$

$$e^{i\theta_6} = \cos\theta_6 + i\sin\theta_6$$

$$e^{i\theta_7} = \cos\theta_7 + i\sin\theta_7$$

Separating the real and imaginary parts of eq (4.64),we get real part

$$c\left(\omega_3^2 \cos\theta_3 + \alpha_3 \sin\theta_3\right) + d\left(\omega_4^2 \cos\theta_4 + \alpha_4 \sin\theta_4\right)$$

$$+f\left(\omega_6^2 \cos\theta_6 + \alpha_6 \sin\theta_6\right) + d\left(\omega_7^2 \cos\theta_7 + \alpha_7 \sin\theta_7\right) = 0 \qquad \text{............}(4.65)$$

$$X_2 = -c\left(\omega_3^2 \cos\theta_3 + \alpha_3 \sin\theta_3\right) - d\left(\omega_4^2 \cos\theta_4 + \alpha_4 \sin\theta_4\right) - f\omega_6^2 \cos\theta_6 - g\omega_7^2 \cos\theta_7$$

$$X_2 + f\alpha_6 \sin\theta_6 + \alpha_7 \sin\theta_7 = 0$$

Imaginary part

$$X_1 = -c\left(\alpha_3 \cos\theta_3 - \omega_3^2 \sin\theta_3\right) - d\left(\alpha_4 \cos\theta_4 - \omega_4^2 \sin\theta_4\right) + f\omega_6^2 \sin\theta_6 + d\omega_7^2 \sin\theta_7$$

$$X_1 + f\alpha_6 \cos\theta_6 + g\alpha_7 \cos\theta_7 = 0$$

By solving the above equations we get

$$X_1 \sin\theta_7 - X_2 \cos\theta_7 + f\alpha_6\left(\sin\theta_7 \cos\theta_6 - \sin\theta_6 \cos\theta_7\right) = 0 \qquad \text{.........}(4.66)$$

By solving above equation (4.66), we get

$$\alpha_6 = \frac{X_1 \sin\theta_7 - X_2 \cos\theta_7}{f * \sin\left(\theta_6 - \theta_7\right)} \qquad \text{.........}(4.67)$$

Similarly for α_7 ,

$$\alpha_7 = \frac{X_1 \sin\theta_6 - X_2 \cos\theta_6}{g * \sin\left(\theta_7 - \theta_6\right)} \qquad \text{.........}(4.68)$$

4.3.3 Acceleration of vector loop equation for loop EDCO$_2$:

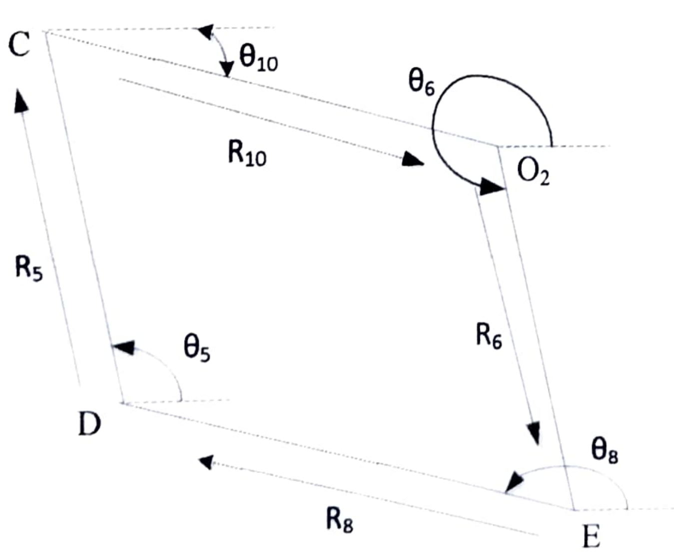


Figure 4.9 The vector loopEDCO$_2$

Differentiating the angular velocity equation (4.51) of third loop,

$$ee^{i\theta_5}\left(i\alpha_5-\omega_5^2\right)+fe^{i\theta_6}\left(i\alpha_6-\omega_6^2\right)+he^{i\theta_8}\left(i\alpha_8-\omega_8^2\right)+je^{i\theta_{10}}\left(i\alpha_{10}-\omega_{10}^2\right)=0 \quad \ldots\ldots\ldots(4.69)$$

$$e^{i\theta_5}=\cos\theta_5+i\sin\theta_5$$

$$e^{i\theta_6}=\cos\theta_6+i\sin\theta_6$$

$$e^{i\theta_8}=\cos\theta_8+i\sin\theta_8$$

$$e^{i\theta_{10}}=\cos\theta_{10}+i\sin\theta_{10}$$

Separating the real and imaginary parts of eq(4.69),we get real part

$$e\left(\omega_5^2\cos\theta_5+\alpha_5\sin\theta_5\right)+f\left(\omega_6^2\cos\theta_6+\alpha_6\sin\theta_6\right)$$
$$+h\left(\omega_8^2\cos\theta_8+\alpha_8\sin\theta_8\right)+j\left(\omega_{10}^2\cos\theta_{10}+\alpha_{10}\sin\theta_{10}\right)=0 \quad \ldots\ldots\ldots(4.70)$$

$$X_3=f\left(\omega_6^2\cos\theta_6+\alpha_6\sin\theta_6\right)+j\left(\omega_{10}^2\cos\theta_{10}+\alpha_{10}\sin\theta_{10}\right)+e\omega_5^2\cos\theta_5+h\omega_8^2\cos\theta_8$$

$$X_3+e\alpha_5\sin\theta_5+h\alpha_8\sin\theta_8=0$$

Imaginary part

$$e\left(\alpha_5\cos\theta_5-\omega_5^2\sin\theta_5\right)+f\left(\alpha_6\cos\theta_6-\omega_6^2\sin\theta_6\right)$$
$$+h\left(\alpha_8\cos\theta_8-\omega_8^2\sin\theta_8\right)+j\left(\alpha_{10}\cos\theta_{10}+\omega_{10}^2\sin\theta_{10}\right)=0 \quad \ldots\ldots\ldots(4.71)$$

$$X_4=f\left(\alpha_6\cos\theta_6-\omega_6^2\sin\theta_6\right)+j\left(\alpha_{10}\cos\theta_{10}-\omega_{10}^2\sin\theta_{10}\right)-e\omega_5^2\sin\theta_5-h\omega_8^2\sin\theta_8$$

$$X_4+e\alpha_5\cos\theta_5+h\alpha_8\cos\theta_8=0$$

$$X_3\cos\theta_8-X_4\sin\theta_8+e\alpha_5\left(\sin\theta_5\cos\theta_8-\cos\theta_5\sin\theta_8\right)=0 \quad \ldots\ldots\ldots(4.72)$$

By solving above equation (4.72), we get

$$\alpha_5=\frac{X_4\sin\theta_8-X_3\cos\theta_8}{e*\sin\left(\theta_5-\theta_8\right)} \quad \ldots\ldots\ldots(4.73)$$

Similarly for α_8,

$$\alpha_8=\frac{X_4\sin\theta_5-X_3\cos\theta_5}{h*\sin\left(\theta_8-\theta_5\right)} \quad \ldots\ldots\ldots(4.74)$$

CHAPTER 5

5. KINEMATIC ANALYSIS OF RIGHT LEG

Here the complex Algebra is used for vectors to develop and derive the equations for angular positions of linkages. From figure (5.1) each loop has been analysed as follows.

5.1 POSITION ANALYSIS OF RIGHT LEG:

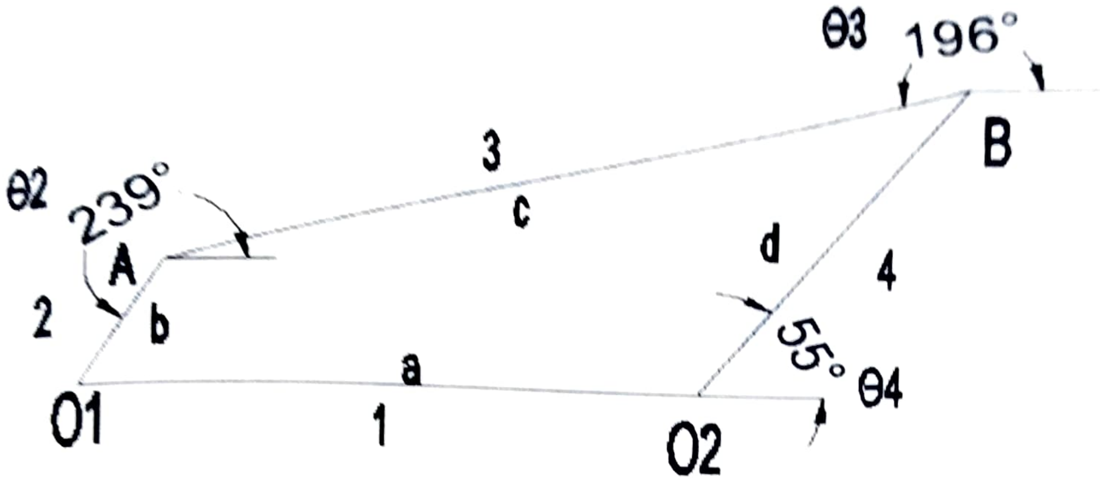


Figure 5.1 The vector loopO_1ABO_2

5.1.1 The vector loop of O_1ABO_2:

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as $O_1O_2 = a, O_1A = b, AB = c, BO_2 = d$ as shown in figure (5.1).

$$ae^{i\theta_1} + be^{i\theta_2} + ce^{i\theta_3} + de^{i\theta_4} = 0 \qquad \text{........ (5.1)}$$

Separating the real and imaginary parts in eq (5.1), the real part is

$$a\cos\theta_1 + b\cos\theta_2 + c\cos\theta_3 + d\cos\theta_4 = 0. \qquad \text{.......... (5.2)}$$

The imaginary part is

$$a\sin\theta_1 + b\sin\theta_2 + c\sin\theta_3 + d\sin\theta_4 = 0 \qquad \text{............ (5.3)}$$

But the angle made by the fixed link is 0°, therefore by substituting $\theta_1 = 0^0$

In eq (4.2) and (4.3) we get,

$$a + b\cos\theta_2 + c\cos\theta_3 + d\cos\theta_4 = 0 \qquad \text{........ (5.4)}$$

$$b\sin\theta_2 + c\sin\theta_3 + d\sin\theta_4 = 0 \quad \text{......... (5.5)}$$

eliminating $\rightarrow \theta_4$ From the above equations (5.4) & (5.5) we get

$$-d\cos\theta_4 = a + b\cos\theta_2 + c\cos\theta_3 \quad \text{......... (5.6)}$$

$$-d\sin\theta_4 = b\sin\theta_2 + c\sin\theta_3 \quad \text{......... (5.7)}$$

Squaring and adding the above equations (5.6) & (5.7)

$$d^2 = a^2 + b^2 + c^2 + 2ab\cos\theta_2 + 2bc\cos\theta_2\cos\theta_3 + 2ac\cos\theta_3 + 2bc\sin\theta_2\sin\theta_3$$

$$\frac{d^2 - a^2 - b^2 - c^2}{2bc} = \frac{a}{c}\cos\theta_2 + \cos\theta_2\cos\theta_3 + \frac{a}{b}\cos\theta_3 + \sin\theta_2\sin\theta_3 \quad \text{......... (5.8)}$$

Let $k_1 = \frac{a}{c}, k_2 = \frac{a}{b}, k_3 = \frac{d^2 - a^2 - b^2 - c^2}{2bc}$

Substituting **k_1, k_2, k_3** in eq (4.8) we get

$$k_3 = k_1\cos\theta_2 + k_2\cos\theta_3 + (\cos\theta_2\cos\theta_3 + \sin\theta_2\sin\theta_3) \quad \text{......... (5.9)}$$

By substituting $\cos\theta_3 = \dfrac{1 - \tan^2\left(\frac{\theta_3}{2}\right)}{1 + \tan^2\left(\frac{\theta_3}{2}\right)}, \sin\theta_3 = \dfrac{2\tan\left(\frac{\theta_3}{2}\right)}{1 + \tan^2\left(\frac{\theta_3}{2}\right)}$ in eq (5.9)

$$A\tan^2\left(\frac{\theta_3}{2}\right) + B\tan\left(\frac{\theta_3}{2}\right) + C = 0 \quad \text{......... (5.10)}$$

By solving the above quadratic equation (4.10) we get

$$\theta_3 = 2\tan^{-1}\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right) \quad \text{......... (5.11)}$$

Similarly for θ_4 ,**we get**

$$\theta_4 = 2\tan^{-1}\left(\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right) \quad \text{......... (5.12)}$$

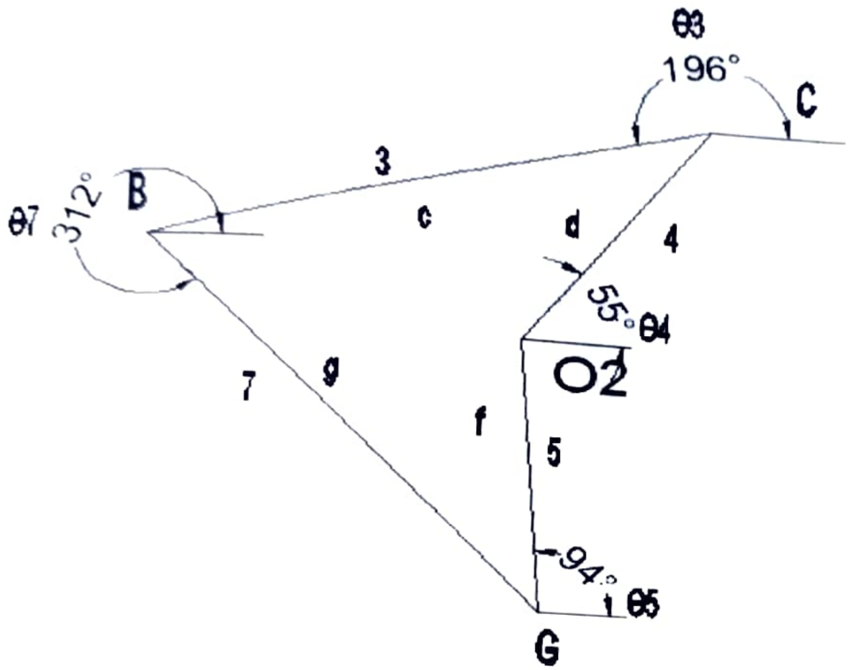


Figure 5.2 The vector loop BGO_2C

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as GO_2=f, BG=g, BC=c, CO_2=d as shown in figure,

$$ge^{i\theta_7}+ce^{i\theta_3}+de^{i\theta_4}+fe^{i\theta_5}=0 \qquad \text{.........} (5.13)$$

Separating the real and imaginary parts in eq (5.13), the real part is

$$g\cos\theta_7+c\cos\theta_3+d\cos\theta_4+f\cos\theta_5=0 \qquad \text{.........} (5.14)$$

The imaginary part is

$$g\sin\theta_7+c\sin\theta_3+d\sin\theta_4+f\cos\theta_5=0 \qquad \text{.........} (5.15)$$

$$M_1 = c\cos\theta_3 + d\cos\theta_4$$

$$M_2 = c\sin\theta_3 + d\sin\theta_4$$

$$M_1+ g\cos\theta_7+ f\cos\theta_5=0 \qquad \text{.........} (5.16)$$

$$M_2+ g\sin\theta_7+f\sin\theta_5=0 \qquad \text{.........} (5.17)$$

eliminating $\rightarrow \theta_7$ From the above equations (5.16) & (5.17) we get

$-g\cos\theta_7 = M_1 + f\cos\theta_5$ .... (5.18)

$-g\sin\theta_7 = M_2 + f\sin\theta_5$ .... (5.19)

Squaring and adding the above equations (5.18) & (5.19)

$g^2 = M_1^2 + M_2^2 + h^2 + 2f(M_1\cos\theta_5 + M_2\sin\theta_5)$

$$M_1\cos\theta_5 + M_2\sin\theta_5 = \frac{g^2 - M_1^2 - M_2^2 - f^2}{2f}$$

$$P_1 = \frac{g^2 - M_1^2 - M_2^2 - f^2}{2f}$$

$P_1 = M_1\cos\theta_5 + M_2\sin\theta_5$ .... (5.20)

By substituting $\cos\theta_5 = \dfrac{1 - tan^2\left(\frac{\theta_5}{2}\right)}{1 + tan^2\left(\frac{\theta_5}{2}\right)}$,

$$\sin\theta_5 = \frac{2tan\left(\frac{\theta_5}{2}\right)}{1 + tan^2\left(\frac{\theta_5}{2}\right)}$$

We get, $G\tan^2\left(\frac{\theta_5}{2}\right) + H\tan^2\left(\frac{\theta_5}{2}\right) + I = 0$ .... (5.21)

$G = P_1 + M_1$

$H = -2M_2$

$I = P_1 - M_1$

By solving the above quadratic equation (5.21), we get

$\theta_5 = 2tan^{-1}\left(\frac{-H \pm \sqrt{H^2 - 4IG}}{2G}\right)$ .... (5.22)

Similarly for θ_7, we get

$$\theta_7 = 2\tan^{-1}\left(\frac{-K \pm \sqrt{K^2 - 4JL}}{2J}\right) \qquad \text{.......... (5.23)}$$

5.1.3 The vector loop EDO_2E:

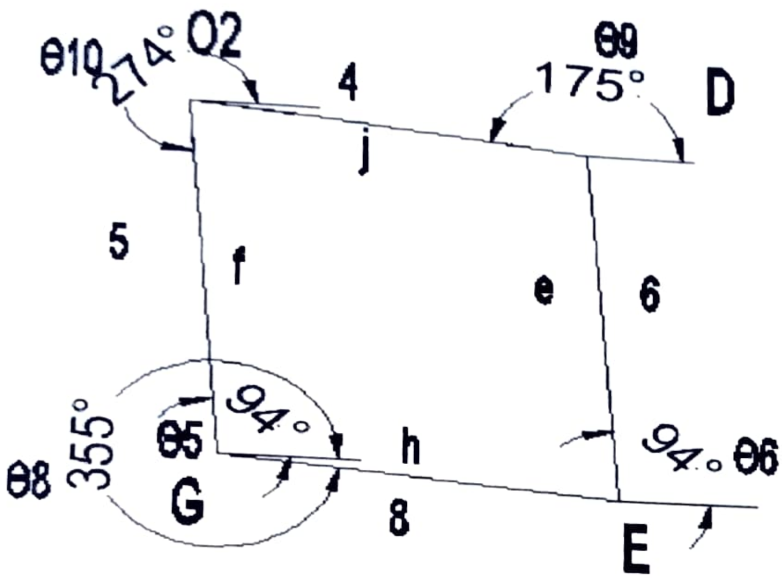


Figure 5.3 The vector loopEDO_2G

Substitute the complex number notation for the vector in above equation, denoting their scalar lengths as DE=e, GE=h, GO_2=f, O_2D=j as shown in figure

$$he^{i\theta_8} + ee^{i\theta_6} + je^{i\theta_9} + fe^{i\theta_{10}} = 0 \qquad \text{.......... (5.24)}$$

Separating the real and imaginary parts in eq (4.13), The real part is

$$h\cos\theta_8 + e\cos\theta_6 + j\cos\theta_9 + f\cos\theta_{10} = 0 \qquad \text{.......... (5.25)}$$

The imaginary part is

$$h\sin\theta_8 + e\sin\theta_6 + j\sin\theta_9 + f\sin\theta_{10} = 0 \qquad \text{.......... (5.26)}$$

$N_1 = h\cos\theta_8 + e\cos\theta_6$

$N_2 = h\sin\theta_8 + e\sin\theta_6$

Where, $\theta_{10} = 180 + \theta_5$, $\theta_9 = 180 + (\theta_4 - \theta_{dj})$

$N_1 + h \cos\theta_8 + e\cos\theta_6 = 0$ .... (5.27)

$N_2 + h \sin\theta_8 + e\sin\theta_6 = 0$ .... (5.28)

Eliminating θ_6 From the above equations (5.27) & (5.28) we get

$-e\cos\theta_6 = N_1 + h\cos\theta_8$ .... (5.29)

$-e\sin\theta_6 = N_2 + h\sin\theta_8$ .... (5.30)

Squaring and adding the above equations (5.29) & (5.30)

$e^2 = N_1^2 + N_2^2 + h^2 + 2h\,(N_1\cos\theta_8 + N_2\sin\theta_8)$

$$N_1\cos\theta_8 + N_2\sin\theta_9 = \frac{e^2 - N_1^2 - N_2^2 - h^2}{2h}$$

$$q_1 = \frac{e^2 - N_1^2 - N_2^2 - h^2}{2h}$$

$q_1 = N_1\cos\theta_8 + N_2\sin\theta_8$ .... (5.31)

By substituting $\cos\theta_8 = \dfrac{1 - \tan^2\left(\frac{\theta_8}{2}\right)}{1 + \tan^2\left(\frac{\theta_8}{2}\right)}$, $\sin\theta_8 = \dfrac{2\tan\left(\frac{\theta_8}{2}\right)}{1 + \tan^2\left(\frac{\theta_8}{2}\right)}$.

We get ,$J\tan^2\left(\frac{\theta_8}{2}\right) + K\tan^2\left(\frac{\theta_8}{2}\right) + L = 0$ ....(5.32)

$J = q_1 + N_1$

$K = -2N_2$

$L = q_1 - N_1$

By solving the above quadratic equation (5.32), we get

$$\theta_8 = 2\tan^{-1}\left(\frac{-K \pm \sqrt{K^2 - 4JL}}{2J}\right)$$ .... (5.33)

Similarly for θ_6, we get

$$\theta_6 = 2tan^{-1}\left(\frac{-Y \pm \sqrt{Y^2 - 4XY}}{2X}\right) \quad (5.34)$$

5.2 VELOCITY ANALYSIS OF RIGHT LEG:

5.2.1 Velocity of the vector loop of O_1ABO_2

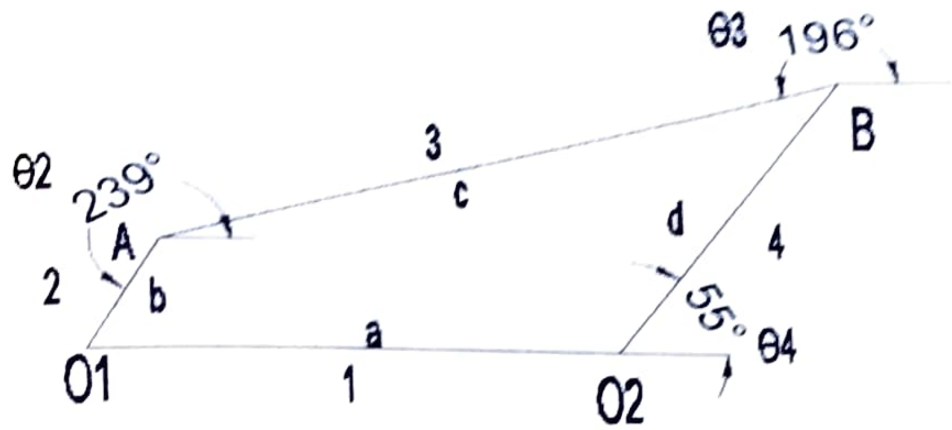


Figure 5.4 The vector loopO_1ABO_2

Differentiating position equation (5.1) of first loop to get the velocity expression

$$b\omega_2 ie^{i\theta_2} + c\omega_3 ie^{i\theta_3} + d\omega_4 ie^{i\theta_4} = 0 \quad ....(5.35)$$

Separating the real and imaginary parts in eq (5.35), The real part is

$$b\omega_2 \cos\theta_2 + c\omega_3 \cos\theta_3 + d\omega_4 \cos\theta_4 = 0 \quad ....(5.36)$$

The imaginary part is

$$b\omega_2 \sin\theta_2 + c\omega_3 \sin\theta_3 + d\omega_4 \sin\theta_4 = 0 \quad ....(5.37)$$

Multiplying eq (5.36) with $\sin\theta_4$ and eq (5.37) with $\cos\theta_4$ we get,

$$b\omega_2 \sin\theta_2 \cos\theta_4 + c\omega_3 \sin\theta_3 \cos\theta_4 + d\omega_4 \sin\theta_4 \cos\theta_4 = 0 \quad ....(5.38)$$

$$b\omega_2 \cos\theta_2 \sin\theta_4 + c\omega_3 \cos\theta_3 \sin\theta_4 + d\omega_4 \cos\theta_4 \sin\theta_4 = 0 \quad ....(5.39)$$

Subtracting the above equations, we get

$$b\omega_2 (\sin\theta_2 \cos\theta_4 - \cos\theta_2 \sin\theta_4) + c\omega_3 (\sin\theta_3 \cos\theta_4 - \cos\theta_3 \sin\theta_4) = 0 \quad .....(5.40)$$

$$b\omega_2\left(\sin\left(\theta_2-\theta_4\right)\right)+c\omega_3\left(\sin\left(\theta_3-\theta_4\right)\right)=0$$

By solving above equation (5.40), we get

$$\omega_3=\frac{b\omega_2\left(\sin\left(\theta_2-\theta_4\right)\right)}{c\left(\sin\left(\theta_4-\theta_3\right)\right)} \qquad \text{.......... (5.41)}$$

Similarly for ω_4,

$$\omega_4=\frac{b\omega_2\left(\sin\left(\theta_2-\theta_3\right)\right)}{d\left(\sin\left(\theta_3-\theta_4\right)\right)} \qquad \text{.......... (5.42)}$$

5.2.2 Velocity of vector loop equation for BGO_2C:

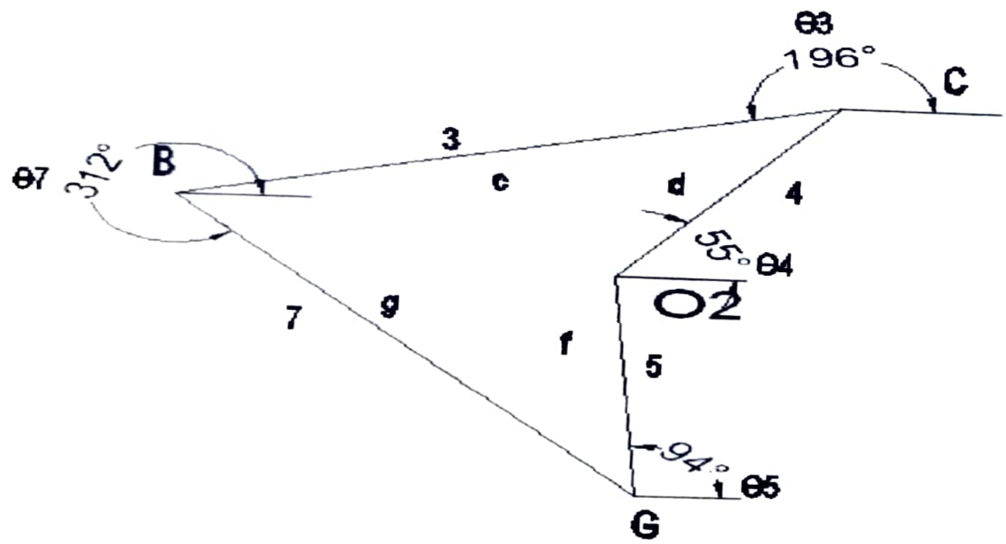


Figure 5.5 The vector loop of BGO_2C

Differentiating position equation (5.13) of second loop to get the velocity expression

$$g\omega_7 ie^{i\theta_7}+c\omega_3 e^{i\theta_3}+d\omega_4 e^{i\theta_4}+f\omega_5 e^{i\theta_5}=0 \qquad \text{.......... (5.43)}$$

Separating the real and imaginary parts in eq (5.43), the real part is

$$g\omega_7\cos\theta_7+c\omega_3\cos\theta_3+d\omega_4\cos\theta_4+f\omega_5\cos\theta_5=0 \qquad \text{.......... (5.44)}$$

The imaginary part

$$g\omega_7\sin\theta_7+c\omega_3\sin\theta_3+d\omega_4\sin\theta_4+f\omega_5\sin\theta_5=0 \qquad \text{.......... (5.45)}$$

Multiplying eq (5.44) with $\sin\theta_7$ and eq (5.45) with $\cos\theta_7$ we get

$g\omega_7 \sin\theta_7 \cos\theta_7 + c\omega_3 \sin\theta_3 \cos\theta_7 + d\omega_4 \sin\theta_4 \cos\theta_7 + f\omega_5 \sin\theta_5 \cos\theta_7 = 0$ ...... (5.46)

$g\omega_7 \cos\theta_7 \sin\theta_7 + c\omega_3 \cos\theta_3 \sin\theta_7 + d\omega_4 \cos\theta_4 \sin\theta_7 + f\omega_5 \cos\theta_5 \sin\theta_7 = 0$ ...... (5.47)

Subtracting the above equations, we get

$c\omega_3(\sin\theta_3 \cos\theta_7 - \cos\theta_3 \sin\theta_7) + d\omega_4 (\sin\theta_4 \cos\theta_7 - \cos\theta_4 \sin\theta_7)$

$+f\omega_5 (\sin\theta_5 \cos\theta_7 - \cos\theta_5 \sin\theta_7) = 0$

.........(5.48)

$c\omega_3 \sin(\theta_3 - \theta_7) + d\omega_4 \sin(\theta_4 - \theta_7) + f\omega_5 \sin(\theta_5 - \theta_7) = 0$

By solving above equation (5.48), we get

$$\omega_5 = \frac{c\omega_3 \sin(\theta_3 - \theta_7) + d\omega_4 \sin(\theta_4 - \theta_7)}{f \sin(\theta_7 - \theta_5)}$$ .... (5.49)

Similarly for ω_7,

$$\omega_7 = \frac{c\omega_3 \sin(\theta_3 - \theta_5) + d\omega_4 \sin(\theta_4 - \theta_5)}{g \sin(\theta_5 - \theta_7)}$$ .... (5.50)

5.2.3 Velocity of vector loop equation for EGO_2D:

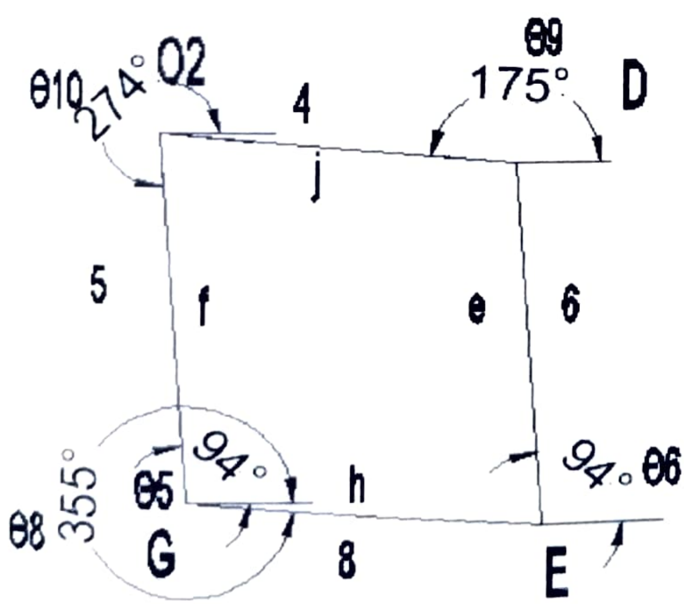


Figure 5.6 The vector loopEGO_2D

Differentiating position equation (5.24) of third loop to get the velocity expression

$h\omega_8 i e^{i\theta_8} + e\omega_6 i e^{i\theta_6} + j\omega_9 i e^{i\theta_9} + f\omega_{10} i e^{i\theta_{10}} = 0$ ………. (5.51)

Separating the real and imaginary parts in eq (5.51), the real part is

$h\omega_8 \cos\theta_8 + e\omega_6 \cos\theta_6 + j\omega_9 \cos\theta_9 + f\omega_{10} \cos\theta_{10} = 0$

The imaginary part

$h\omega_8 \sin\theta_8 + e\omega_6 \sin\theta_6 + j\omega_9 \sin\theta_9 + f\omega_{10} \sin\theta_{10} = 0$

Let

$j\omega_9 \cos\theta_9 + f\omega_{10} \cos\theta_{10} = S_1$ ………… (5.52)

$j\omega_9 \sin\theta_9 + f\omega_{10} \sin\theta_{10} = S_2$

$h\omega_8 \cos\theta_8 + e\omega_6 \cos\theta_6 + S_1 = 0$ ………… (5.52)

$h\omega_8 \sin\theta_8 + e\omega_6 \sin\theta_6 + S_2 = 0.$ ………. (5.53)

Multiplying eq (5.52) with $\sin\theta_8$ and eq (5.53) with $\cos\theta_8$ we get

$h\omega_8 \cos\theta_8 \sin\theta_8 + e\omega_6 \cos\theta_6 \sin\theta_8 + S_1 \sin\theta_8 = 0$ …..(5.55)

$h\omega_8 \sin\theta_8 \cos\theta_8 + e\omega_6 \sin\theta_6 \cos\theta_8 + S_2 \cos\theta_8 = 0$ ….(5.54)

Subtracting the above equations, we get

$e\omega_6 (\cos\theta_6 \sin\theta_8 - \sin\theta_6 \cos\theta_8) + S_1 \sin\theta_8 - S2 \cos\theta_8 = 0$

$e\omega_6 \sin(\theta_6 - \theta_8) = S_1 \sin\theta_8 - S2 \cos\theta_8$

$$\omega_6 = \frac{S1 \sin\theta_8 - S2 \cos\theta_8}{e \sin(\theta_6 - \theta_8)} \quad \text{……… (5.57)}$$

Similarly for, ω_8

$$\omega_8 = \frac{S1 \sin\theta_6 - S2 \cos\theta_6}{h \sin(\theta_8 - \theta_6)} \quad \text{……… (5.58)}$$

5.3 ACCELERATION ANALYSIS OF RIGHT LEG:

5.3.1 Acceleration of vector loop equation for loop O_1ABO_2:

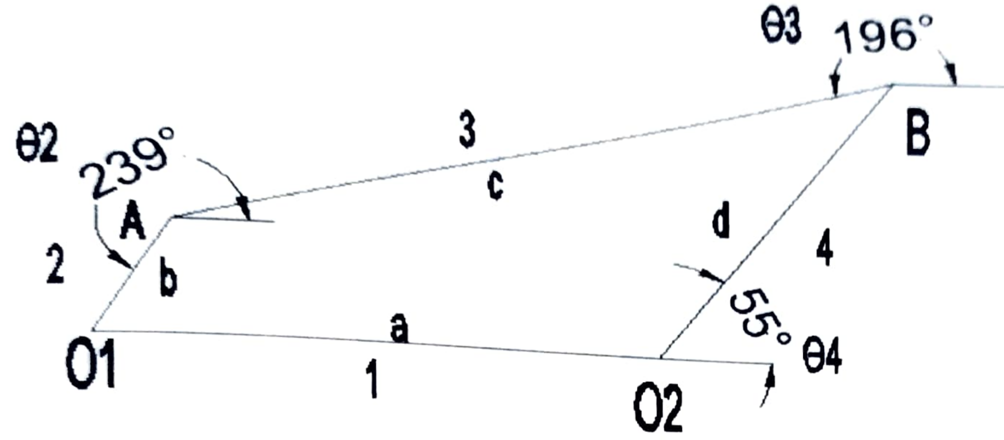


Figure 5.7 The vector loopO_1ABO_2

Differentiating the angular velocity equation (5.35) of first loop,

$$be^{i\theta_2}\left(i\alpha_2-\omega_2^2\right)+ce^{i\theta_3}\left(i\alpha_3-\omega_3^2\right)+de^{i\theta_4}\left(i\alpha_4-\omega_4^2\right)=0 \qquad \text{..........(5.59)}$$

$$e^{i\theta_2}=\cos\theta_2+i\sin\theta_2$$

$$e^{i\theta_3}=\cos\theta_3+i\sin\theta_3$$

$$e^{i\theta_4}=\cos\theta_4+i\sin\theta_4$$

Separating the real and imaginary parts of eq(5.59),we get real part,

$$b\left(\omega_2^2\cos\theta_2+\alpha_2\sin\theta_2\right)+c\left(\omega_3^2\cos\theta_3+\alpha_3\sin\theta_3\right)+d\left(\omega_4^2\cos\theta_4+\alpha_4\sin\theta_4\right)=0 \text{...(5.60)}$$

$$Y_2=b\omega_2^2\cos\theta_2+b\alpha_2\sin\theta_2+c\omega_3^2\cos\theta_3+d\omega_4^2\cos\theta_4$$

$$Y_2+c\alpha_3\sin\theta_3+d\alpha_4\sin\theta_4=0$$

Imaginary part

$$Y_1=b\alpha_2\cos\theta_2-b\omega_2^2\sin\theta_2-c\omega_3^2\sin\theta_3-d\omega_4^2\sin\theta_4$$

$$Y_1+c\alpha_3\cos\theta_3+d\alpha_4\cos\theta_4=0$$

By solving the above equations we get,

$$Y_2\cos\theta_4-Y_1\sin\theta_4+c\alpha_3\sin\left(\theta_3-\theta_4\right)=0 \qquad \text{..........(5.61)}$$

By solving above equation (5.61), we get

$$\alpha_3 = \frac{Y_2 \cos\theta_4 - Y_1 \sin\theta_4}{c \sin(\theta_4 - \theta_3)} \quad \text{.........(5.62)}$$

Similarly for α_4,

$$\alpha_4 = \frac{Y_2 \cos\theta_3 - Y_1 \sin\theta_3}{d \sin(\theta_3 - \theta_4)} \quad \text{.........(5.63)}$$

5.3.2 Acceleration of vector loop equation for loop BGO$_2$C:

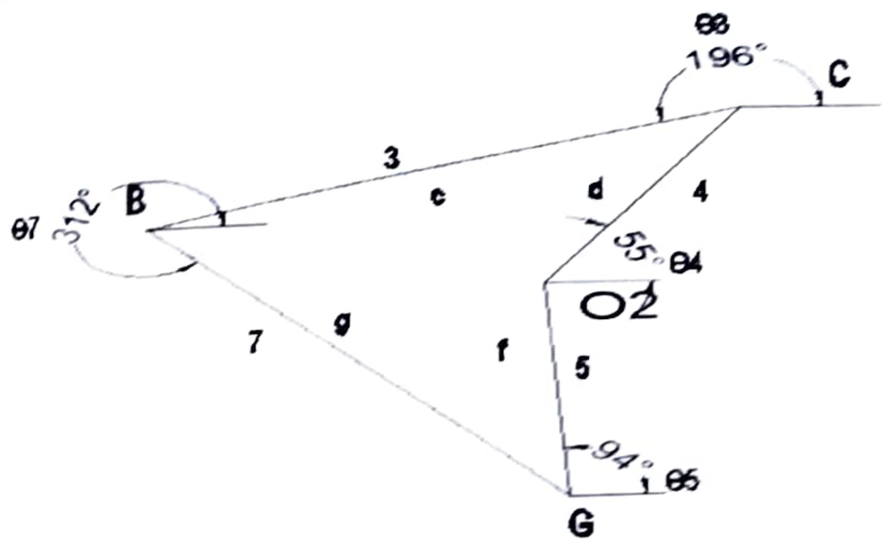


Figure 5.8 The vector loop BGO$_2$C

Differentiating the angular velocity equation (5.43) of second loop

$$ge^{i\theta_7}(i\alpha_7 - \omega_7^2) + ce^{i\theta_3}(i\alpha_3 - \omega_3^2) + de^{i\theta_4}(i\alpha_4 - \omega_4^2) + fe^{i\theta_5}(i\alpha_5 - \omega_5^2) = 0 \quad \text{.........(5.64)}$$

$$e^{i\theta_3} = \cos\theta_3 + i\sin\theta_3$$

$$e^{i\theta_4} = \cos\theta_4 + i\sin\theta_4$$

$$e^{i\theta_5} = \cos\theta_5 + i\sin\theta_5$$

$$e^{i\theta_7} = \cos\theta_7 + i\sin\theta_7$$

Separating the real and imaginary parts of eq (5.64),we get real part

$$g\alpha_7 \sin\theta_7 + g\omega_7^2 \cos\theta_7 + c\alpha_3 \sin\theta_3 +$$
$$c\omega_3^2 \cos\theta_3 + d\alpha_4 \sin\theta_4 + d\omega_4^2 \cos\theta_4 + f\alpha_5 \sin\theta_5 + f\omega_5^2 \cos\theta_5 = 0$$

Imaginary part

$$g\alpha_7 \cos\theta_7 - g\omega_7^2 \sin\theta_7 + c\alpha_3 \cos\theta_3 c\omega_3^2 -$$
$$\sin\theta_3 + d\alpha_4 \cos\theta_4 - d\omega_4^2 \sin\theta_4 + f\alpha_5 \cos\theta_5 - f\omega_5^2 \sin\theta_5 = 0$$

$X_1 = -c\omega_3^2\ sin\theta_3 + c\alpha_3\ cos\theta_3 - d\omega_4^2\ sin\theta_4 + d\alpha_4 cos\ \theta_4 - g\omega_7^2\ sin\theta_7 -$
$f\omega_5^2\ sin\theta_5 = 0$

$X_1 + g\alpha_7\ cos\theta_7 + f\alpha_5\ cos\theta_5 = 0$ ....(5.65)

$X_2 = c\omega_3^2\ cos\theta_3 + c\alpha_3\ sin\theta_3 + d\omega_4^2\ cos\theta_4 + d\alpha_4 sin\ \theta_4 + g\omega_7^2\ cos\theta_7 +$
$f\omega_5^2\ cos\theta_5 = 0$

$X_2 + g\alpha_7\ sin\theta_7 + f\alpha_5\ sin\theta_5 = 0$ ....(5.66)

Multiplying the eq (5.65) with $\sin\theta_7$ and eq (5.66) with $\cos\theta_7$,we get

$X_1\ sin\theta_7 + g\alpha_7\ cos\theta_7 sin\theta_7 + f\alpha_5\ cos\theta_5 sin\theta_7 = 0$

$X_2\ cos\theta_7 + g\alpha_7\ sin\theta_7\ cos\theta_7 + f\alpha_5\ sin\theta_5 cos\theta_7 = 0$

By solving the above equations we get

$X_1\ sin\theta_7 - X2\ cos\theta_7 = -f\alpha_5(\ sin(\theta_5 - \theta_7))$ ....(5.67)

$$\alpha_5 = \frac{X_2 cos\theta_7 - X_1\ sin\theta_7}{f sin(\theta_7 - \theta_5)}$$ ....(5.68)

Similarly for α_7 ,

$$\alpha_7 = \frac{X_2 cos\theta_5 - X_1\ sin\theta_5}{g sin(\theta_5 - \theta_7)}$$ . ...(5.69)

5.3.3 Acceleration of vector loop equation for loop EGO_2D:

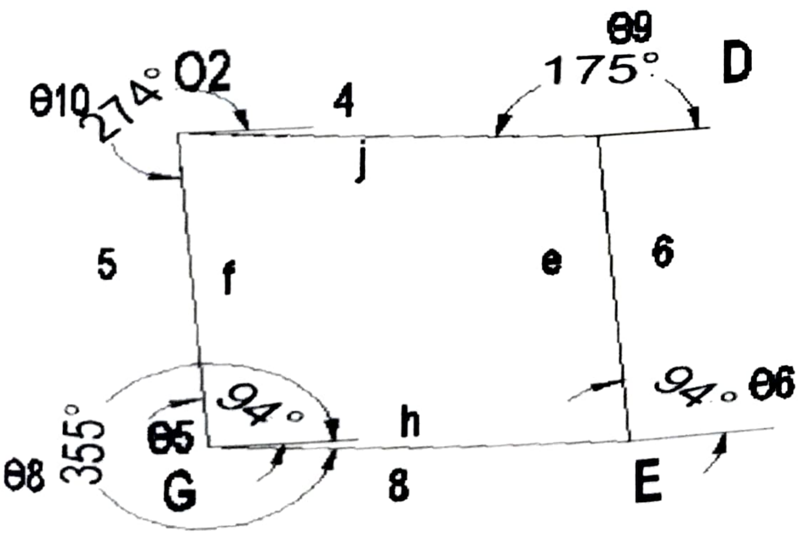


Figure 5.9 The vector loop EGO_2D

Differentiating the angular velocity equation (5.51) of third loop,

$$ee^{i\theta_6}(i\alpha_6-\omega_6^2) + he^{i\theta_8}(i\alpha_8-\omega_8^2)+je^{i\theta_9}(i\alpha_9-\omega_9^2)+fe^{i\theta_{10}}(i\alpha_{10}-\omega_{10}^2)=0 \quad \text{......(5.70)}$$

$$e^{i\theta_6} = cos\theta_6 + i\, sin\theta_6$$

$$e^{i\theta_8} = cos\theta_8 + i\, sin\theta_8$$

$$e^{i\theta_9} = cos\theta_9 + i\, sin\theta_9$$

$$e^{i\theta_{10}} = cos\theta_{10} + i\, sin\theta_{10}$$

Separating the real and imaginary parts of eq (5.64), we get real part

$$h\alpha_8\, sin\theta_8 + h\omega_8^2\, cos\theta_8 + e\alpha_6\, sin\theta_6 + e\omega_6^2\, cos\theta_6 + j\alpha_9\, sin\theta_9 + j\omega_9^2\, cos\theta_9 + f\alpha_{10}\, sin\theta_{10} + f\omega_{10}^2\, cos\theta_{10} = 0$$

Imaginary part

$$h\alpha_8\, cos\theta_8 - h\omega_8^2\, sin\theta_8 + e\alpha_6\, cos\theta_6 - e\omega_6^2\, sin\theta_6 + j\alpha_9\, cos\theta_9 - j\omega_9^2\, sin\theta_9 + f\alpha_{10}\, cos\theta_{10} - f\omega_{10}^2\, sin\theta_{10} = 0$$

$$Z_1 = j\alpha_9\, cos\theta_9 - j\omega_9^2\, sin\theta_9 + f\alpha_{10}\, cos\theta_{10} - f\omega_{10}^2\, sin\theta_{10} - h\omega_8^2\, sin\theta_8 - e\omega_6^2\, sin\theta_6$$

$$Z_1 + h\alpha_8\, cos\theta_8 + e\alpha_6\, cos\theta_6 = 0 \quad \text{......(5.71)}$$

$$Z_2 = h\omega_8^2\, cos\theta_8 + e\omega_6^2\, cos\theta_6 + j\alpha_9\, sin\theta_9 + j\omega_9^2\, cos\theta_9 + f\alpha_{10}\, sin\theta_{10} + f\omega_{10}^2\, cos\theta_{10}$$

$$Z_2 + h\alpha_8\, sin\theta_8 + e\alpha_6\, sin\theta_6 = 0 \quad \text{......(5.72)}$$

Multiplying the eq (5.71) with $sin\theta_8$ and eq (5.72) with $cos\theta_8$, we get

$$Z_1\, sin\theta_8 + h\alpha_8\, cos\theta_8\, sin\theta_8 + e\alpha_6\, cos\theta_6\, sin\theta_8 = 0$$

$$Z_2\, cos\theta_8 + h\alpha_8\, sin\theta_8 cos\theta_8 + e\alpha_6\, sin\theta_6 cos\theta_8 = 0$$

By solving the above equations we get

$$Z_1\, sin\theta_8 - Z_2 cos\theta_8 = -e\alpha_6(sin(\theta_6 - \theta_8)) \quad \text{......(5.73)}$$

$$\alpha_6 = \frac{Z_1\, cos\theta_8 - Z_2\, sin\theta_8}{e sin(\theta_6 - \theta_8)} \quad \text{......(5.74)}$$

Similarly for α_8,

$$\alpha_8 = \frac{Z_1\, cos\theta_6 - Z_2\, sin\theta_6}{h sin(\theta_8 - \theta_6)} \quad \text{......(5.75)}$$

CHAPTER 6

6.RESULTS AND DISCUSSIONS

6.1 KINEMATIC ANALYSIS:

To Track the paths of Two-LeggedTheo Jansen's mechanism for moving joints, **MATLAB** code is developed.

6.1.1 Path traced by the moving joints of left leg:

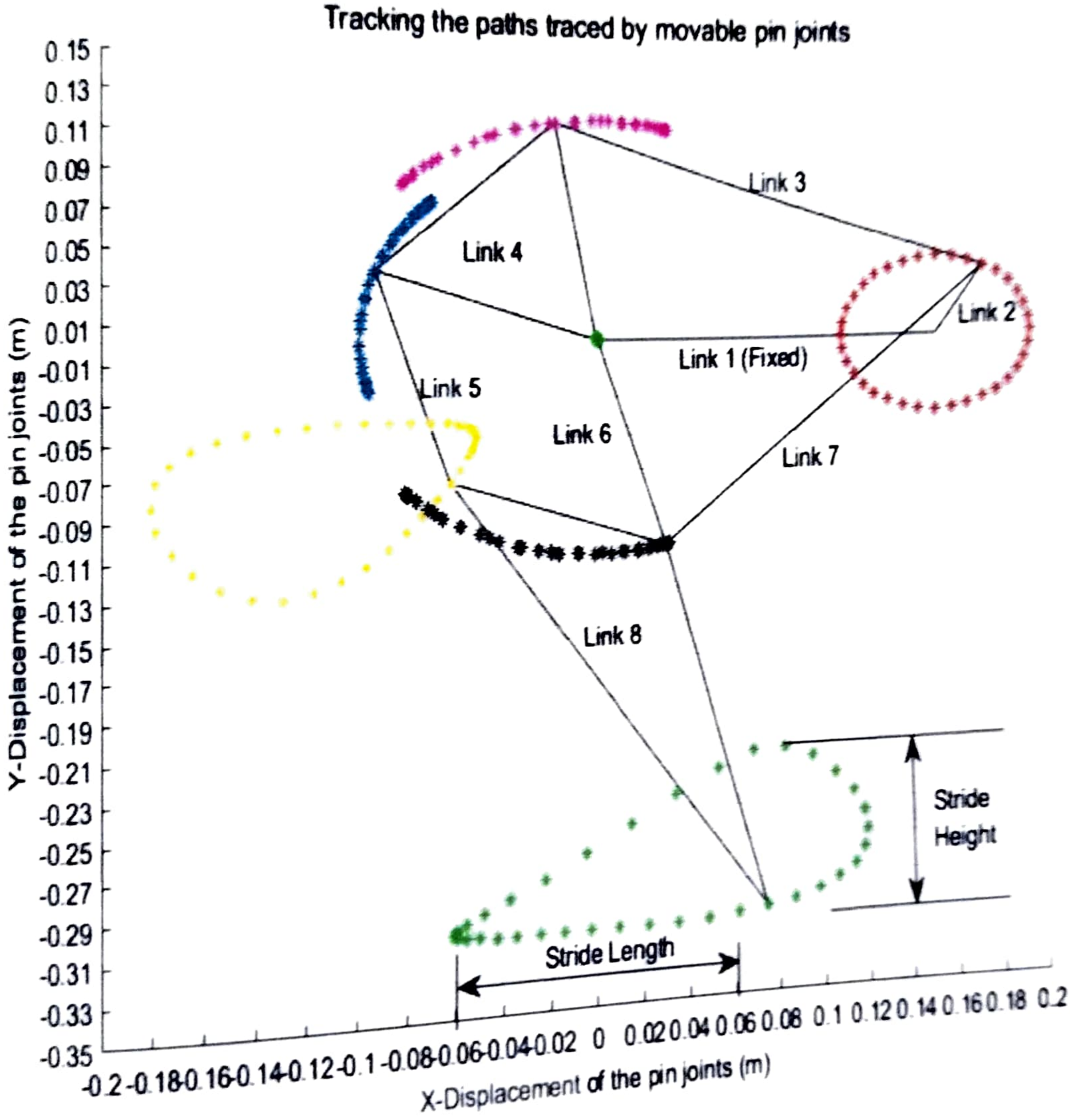


Figure 6.1 Tracking the Paths Traced By Movable Joints of left leg

6.1.2 Results of Angular Positions of left leg:

Table 6.1 Angular Position Analysis of left leg

SL NO	CRANK ANGLE(deg)	Link 3 (deg)	Link4 (deg)	Link5 (deg)	link 6 (deg)	Link 7 (deg)	Link8 (deg)
1	0	146.5847	-101.12	-78.8803	33.41526	101.367	138.6562
2	10	148.7262	-98.7243	-76.9349	35.61454	103.3099	141.0552
3	20	150.784	-95.9097	-75.4678	37.83847	104.7698	143.8803
4	30	152.7384	-92.7101	-74.5057	40.04583	105.7213	147.0959
5	40	154.5747	-89.1636	-74.0751	42.18652	106.139	150.6625
6	50	156.282	-85.3125	-74.2047	44.20078	105.9958	154.5363
7	60	157.8519	-81.2034	-74.9262	46.01847	105.261	158.6695
8	70	159.2763	-76.8882	-76.2772	47.55831	103.8981	163.0094
9	80	160.5464	-72.4251	-78.3011	48.72744	101.8642	167.4974
10	90	161.6502	-67.8808	-81.0473	49.4217	99.11014	172.0668
11	100	162.5696	-63.3345	-84.5683	49.52761	95.58416	176.6386
12	110	163.2771	-58.8837	-88.9112	48.92794	91.23942	-178.884
13	120	163.7308	-54.6535	-94.1021	47.51355	86.05058	-174.625
14	130	163.867	-50.8106	-100.117	45.20573	80.04294	-170.75
15	140	163.5912	-47.5824	-106.834	41.9927	73.33892	-167.486
16	150	162.7696	-45.2773	-113.973	37.97964	66.21951	-165.14
17	160	161.2309	-44.2901	-121.042	33.43681	59.17762	-164.107
18	170	158.8028	-45.0493	-127.345	28.80328	52.90158	-164.827
19	180	155.4092	-47.8555	-132.144	24.59075	48.11356	-167.616
20	190	151.1967	-52.6553	-134.951	21.19723	45.29553	-172.433
21	200	146.5632	-58.9578	-135.71	18.76912	44.50993	-178.775
22	210	142.0204	-66.0266	-134.723	17.23039	45.47026	174.1112
23	220	138.0073	-73.1663	-132.418	16.40877	47.75499	166.9299
24	230	134.7943	-79.8834	-129.189	16.13297	50.97018	160.1768
25	240	132.4865	-85.8979	-125.346	16.26916	54.8062	154.1306
26	250	131.0721	-91.0888	-121.116	16.72288	59.03437	148.9111
27	260	130.4724	-95.4317	-116.665	17.43045	63.48699	144.5415
28	270	130.5783	-98.9527	-112.119	18.34984	68.03828	140.9949
29	280	131.2726	-101.699	-107.575	19.45358	72.5903	138.2235
30	290	132.4417	-103.723	-103.112	20.72372	77.06351	136.1748
31	300	133.9815	-105.074	-98.7966	22.14814	81.39068	134.7992
32	310	135.7992	-105.795	-94.6875	23.71795	85.51299	134.0535
33	320	137.8135	-105.925	-90.8364	25.4253	89.37774	133.9013
34	330	139.9542	-105.494	-87.2899	27.26161	92.93707	134.3117
35	340	142.1615	-104.532	-84.0903	29.21598	96.14735	135.2578
36	350	144.3855	-103.065	-81.2757	31.27377	98.9691	136.7144
37	360	146.5847	-101.12	-78.8803	33.41526	101.367	138.6562

6.1.3 Results of Angular Velocity Analysis of left leg:

Table 6.2 Angular Velocity Analysis of left leg

SL NO	CRANK ANGLE(deg)	Link 3 (rad/s)	Link 4 (rad/s)	link 5 (rad/s)	Link 6 (rad/s)	Link 7 (rad/s)	Link 8 (rad/s)
1	0	6.525822	6.525822	6.525822	6.525822	6.525822	6.525822
2	10	6.310215	7.831239	5.132296	6.65332	5.117425	7.852798
3	20	6.026708	9.039326	3.657079	6.669697	3.629663	9.07983
4	30	5.692273	10.13911	2.102629	6.549462	2.06655	10.19423
5	40	5.3202	11.11857	0.466455	6.264823	0.426057	11.18353
6	50	4.919673	11.96486	-1.25948	5.785712	-1.30027	12.03552
7	60	4.49535	12.66379	-3.08864	5.079794	-3.12678	12.73717
8	70	4.046858	13.19849	-5.03884	4.1128	-5.07213	13.2729
9	80	3.568034	13.54713	-7.12927	2.849825	-7.15619	13.62204
10	90	3.045643	13.67923	-9.37485	1.258737	-9.39418	13.75507
11	100	2.457213	13.55014	-11.7754	-0.68243	-11.7859	13.62821
12	110	1.767533	13.09285	-14.2966	-2.97127	-14.2966	13.17526
13	120	0.923402	12.20605	-16.8389	-5.55625	-16.8261	12.29582
14	130	-0.15301	10.73877	-19.1909	-8.29915	-19.1618	10.83979
15	140	-1.5686	8.476884	-20.9746	-10.9292	-20.925	8.593171
16	150	-3.44833	5.15404	-21.6171	-13.0147	-21.5449	5.286131
17	160	-5.87518	0.546654	-20.4398	-14.018	-20.3542	0.681036
18	170	-8.73894	-5.26509	-16.9906	-13.5168	-16.9254	-5.17084
19	180	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512
20	190	-13.5168	-16.9906	-5.26509	-8.73894	-5.33034	-17.0849
21	200	-14.018	-20.4398	0.546654	-5.87518	0.461023	-20.5742
22	210	-13.0147	-21.6171	5.15404	-3.44833	5.081815	-21.7492
23	220	-10.9292	-20.9746	8.476884	-1.5686	8.427217	-21.0909
24	230	-8.29915	-19.1909	10.73877	-0.15301	10.70962	-19.2919
25	240	-5.55625	-16.8389	12.20605	0.923402	12.19324	-16.9287
26	250	-2.97127	-14.2966	13.09285	1.767533	13.09291	-14.379
27	260	-0.68243	-11.7754	13.55014	2.457213	13.56066	-11.8534
28	270	1.258737	-9.37485	13.67923	3.045643	13.69856	-9.45069
29	280	2.849825	-7.12927	13.54713	3.568034	13.57405	-7.20418
30	290	4.1128	-5.03884	13.19849	4.046858	13.23179	-5.11324
31	300	5.079794	-3.08864	12.66379	4.49535	12.70193	-3.16202
32	310	5.785712	-1.25948	11.96486	4.919673	12.00566	-1.33014
33	320	6.264823	0.466455	11.11857	5.3202	11.15897	0.401489
34	330	6.549462	2.102629	10.13911	5.692273	10.17518	2.047509
35	340	6.669697	3.657079	9.039326	6.026708	9.066741	3.616575
36	350	6.65332	5.132296	7.831239	6.310215	7.84611	5.110737
37	360	6.525822	6.525822	6.525822	6.525822	6.525822	6.525822

6.1.4 Results of Angular Acceleration Analysis of left leg:

Table 6.3 Angular Acceleration Analysis of left leg

SL NO	CRANK ANGLE(deg)	link3 (rad/s^2)	link4 (rad/s^2)	link5 (rad/s^2)	link6 (rad/s^2)	link7 (rad/s^2)	link8 (rad/s^2)
1	0	-30.109	232.1877	-232.188	30.10904	-234.816	235.9742
2	10	-43.4308	216.3144	-246.684	13.06143	-249.099	219.8616
3	20	-53.5443	198.6785	-260.385	-8.16224	-262.237	201.594
4	30	-61.0442	179.0532	-274.065	-33.9677	-275.179	181.1504
5	40	-66.6008	157.2946	-288.641	-64.7452	-289.025	158.6014
6	50	-70.9554	133.2366	-305.08	-100.888	-304.859	133.9222
7	60	-74.9248	106.5606	-324.259	-142.774	-323.591	106.847
8	70	-79.4284	76.64184	-346.734	-190.663	-345.755	76.74292
9	80	-85.5523	42.35366	-372.362	-244.456	-371.158	42.45191
10	90	-94.6666	1.801347	-399.656	-303.189	-398.253	2.050234
11	100	-108.614	-48.0642	-424.687	-364.137	-423.047	-47.5241
12	110	-129.984	-111.998	-439.325	-421.338	-437.347	-111.02
13	120	-162.419	-197.14	-428.773	-463.494	-426.294	-195.563
14	130	-210.704	-313.415	-369.084	-471.795	-365.919	-311.114
15	140	-279.669	-472.023	-227.507	-419.861	-223.663	-469.154
16	150	-369.349	-677.441	27.02321	-281.068	30.63982	-675.251
17	160	-462.452	-905.388	392.3599	-50.5756	392.5821	-907.696
18	170	-507.982	-1071.72	785.9999	222.2593	778.2369	-1083.79
19	180	-434.362	-1048.79	1048.79	434.3621	1035.637	-1067.3
20	190	-222.259	-786	1071.723	507.9822	1063.96	-798.07
21	200	50.57563	-392.36	905.3876	462.4521	905.6098	-394.669
22	210	281.0683	-27.0232	677.4411	369.3495	681.0577	-24.8327
23	220	419.8612	227.5073	472.0226	279.6687	475.8665	230.3756
24	230	471.7949	369.0839	313.4152	210.7042	316.5802	371.3851
25	240	463.4935	428.7728	197.1399	162.4192	199.6191	430.3495
26	250	421.3383	439.3246	111.9979	129.9841	113.9755	440.3027
27	260	364.1371	424.6873	48.06421	108.6144	49.70412	425.2274
28	270	303.1885	399.6565	-1.80135	94.66655	-0.39796	399.9053
29	280	244.4558	372.3618	-42.3537	85.5523	-41.1501	372.46
30	290	190.6634	346.7337	-76.6418	79.4284	-75.6635	346.8347
31	300	142.7737	324.2591	-106.561	74.92476	-105.893	324.5454
32	310	100.8881	305.08	-133.237	70.95535	-133.015	305.7656
33	320	64.74515	288.6405	-157.295	66.60077	-157.679	289.9473
34	330	33.96768	274.065	-179.053	61.04418	-180.167	276.1622
35	340	8.162237	260.3851	-198.679	53.54429	-200.53	263.3005
36	350	-13.0614	246.6838	-216.314	43.43081	-218.73	250.231
37	360	-30.109	232.1877	-232.188	30.10904	-234.816	235.9742

6.1.5 Path traced by the moving joints of right leg:

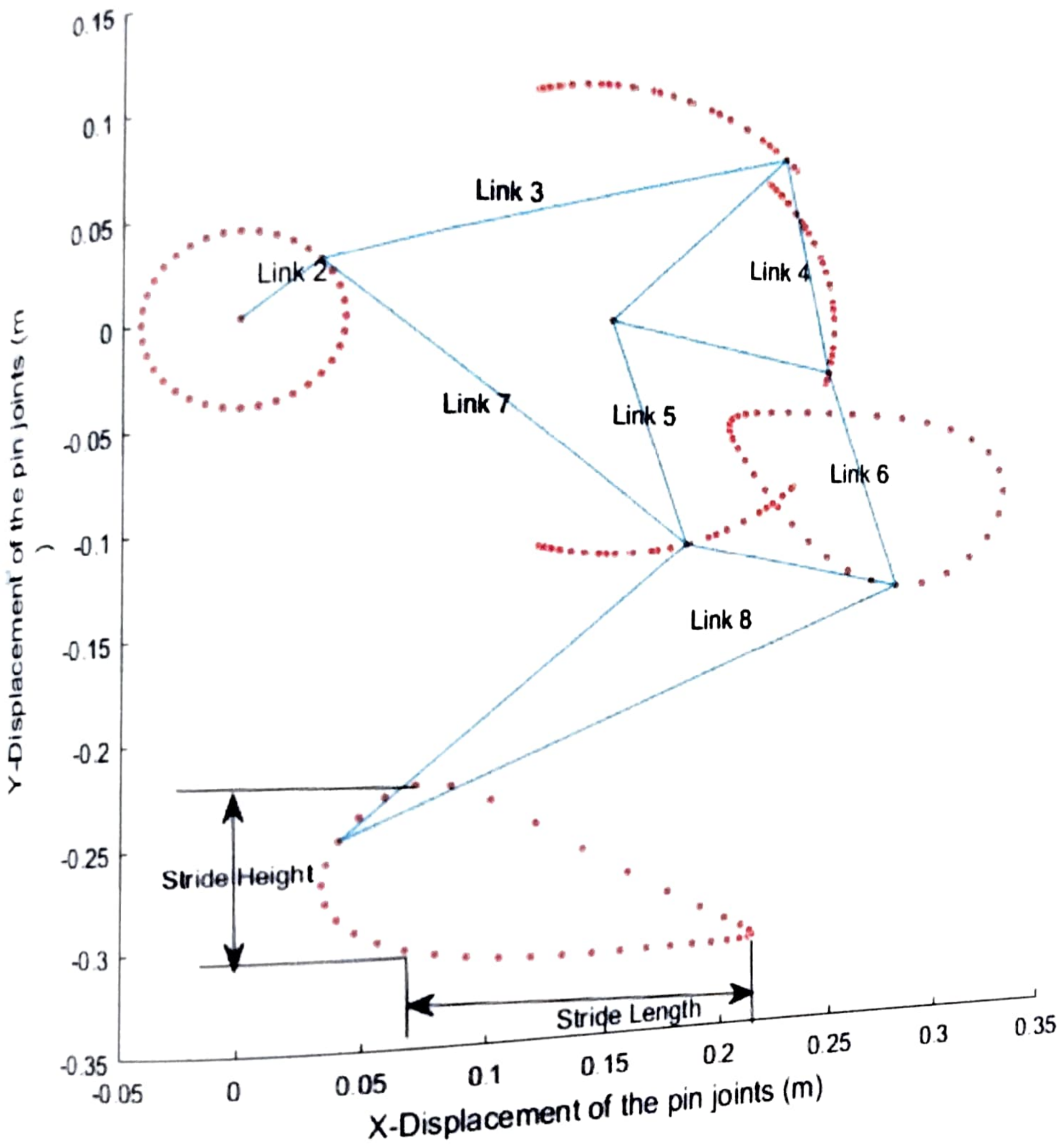


Figure 6.2 Tracking the Paths Traced by Movable Joints of right leg

6.1.6 Results of Angular Positions of right leg:

Table 6.4 Angular Position Analysis of right leg

SL NO	CRANK ANGLE(deg)	Link 3 (deg)	Link 4 (deg)	Link 5 (deg)	Link 6 (deg)	Link 7 (deg)	Link 8 (deg)
1	0	-155.409	47.85553	132.1445	132.1445	-24.5908	-12.1169
2	10	-158.803	45.04928	127.3447	127.3447	-28.8033	-14.9231
3	20	-161.231	44.29014	121.0422	121.0422	-33.4368	-15.6823
4	30	-162.77	45.27732	113.9734	113.9734	-37.9796	-14.6951
5	40	-163.591	47.58239	106.8337	106.8337	-41.9927	-12.39
6	50	-163.867	50.81061	100.1166	100.1166	-45.2057	-9.16179
7	60	-163.731	54.65351	94.10211	94.10211	-47.5135	-5.31889
8	70	-163.277	58.88372	88.91122	88.91122	-48.9279	-1.08868
9	80	-162.57	63.33453	84.5683	84.5683	-49.5276	3.362135
10	90	-161.65	67.8808	81.04733	81.04733	-49.4217	7.908409
11	100	-160.546	72.42508	78.30107	78.30107	-48.7274	12.45268
12	110	-159.276	76.88822	76.2772	76.2772	-47.5583	16.91582
13	120	-157.852	81.20343	74.92625	74.92625	-46.0185	21.23103
14	130	-156.282	85.31251	74.20466	74.20466	-44.2008	25.34012
15	140	-154.575	89.16364	74.07514	74.07514	-42.1865	29.19124
16	150	-152.738	92.7101	74.50568	74.50568	-40.0458	32.73771
17	160	-150.784	95.90968	75.46784	75.46784	-37.8385	35.93728
18	170	-148.726	98.72429	76.93494	76.93494	-35.6145	38.75189
19	180	-146.585	101.1197	78.8803	78.8803	-33.4153	41.1473
20	190	-144.385	103.0651	81.27571	81.27571	-31.2738	43.09266
21	200	-142.162	104.5322	84.09032	84.09032	-29.216	44.55977
22	210	-139.954	105.4943	87.2899	87.2899	-27.2616	45.52193
23	220	-137.813	105.9249	90.83636	90.83636	-25.4253	45.95246
24	230	-135.799	105.7953	94.68749	94.68749	-23.718	45.82295
25	240	-133.982	105.0738	98.79657	98.79657	-22.1481	45.10136
26	250	-132.442	103.7228	103.1118	103.1118	-20.7237	43.75041
27	260	-131.273	101.6989	107.5749	107.5749	-19.4536	41.72654
28	270	-130.578	98.95267	112.1192	112.1192	-18.3498	38.98027
29	280	-130.472	95.4317	116.6655	116.6655	-17.4304	35.4593
30	290	-131.072	91.08878	121.1163	121.1163	-16.7229	31.11638
31	300	-132.486	85.89789	125.3465	125.3465	-16.2692	25.9255
32	310	-134.794	79.88337	129.1894	129.1894	-16.133	19.91097
33	320	-138.007	73.16632	132.4176	132.4176	-16.4088	13.19392
34	330	-142.02	66.02657	134.7227	134.7227	-17.2304	6.054174
35	340	-146.563	58.95782	135.7099	135.7099	-18.7691	-1.01457
36	350	-151.197	52.65532	134.9507	134.9507	-21.1972	-7.31707
37	360	-155.409	47.85553	132.1445	132.1445	-24.5908	-12.1169

6.1.6 Results of Angular Positions of right leg:

Table 6.4 Angular Position Analysis of right leg

SL NO	CRANK ANGLE(deg)	Link 3 (deg)	Link 4 (deg)	Link 5 (deg)	Link 6 (deg)	Link 7 (deg)	Link 8 (deg)
1	0	-155.409	47.85553	132.1445	132.1445	-24.5908	-12.1169
2	10	-158.803	45.04928	127.3447	127.3447	-28.8033	-14.9231
3	20	-161.231	44.29014	121.0422	121.0422	-33.4368	-15.6823
4	30	-162.77	45.27732	113.9734	113.9734	-37.9796	-14.6951
5	40	-163.591	47.58239	106.8337	106.8337	-41.9927	-12.39
6	50	-163.867	50.81061	100.1166	100.1166	-45.2057	-9.16179
7	60	-163.731	54.65351	94.10211	94.10211	-47.5135	-5.31889
8	70	-163.277	58.88372	88.91122	88.91122	-48.9279	-1.08868
9	80	-162.57	63.33453	84.5683	84.5683	-49.5276	3.362135
10	90	-161.65	67.8808	81.04733	81.04733	-49.4217	7.908409
11	100	-160.546	72.42508	78.30107	78.30107	-48.7274	12.45268
12	110	-159.276	76.88822	76.2772	76.2772	-47.5583	16.91582
13	120	-157.852	81.20343	74.92625	74.92625	-46.0185	21.23103
14	130	-156.282	85.31251	74.20466	74.20466	-44.2008	25.34012
15	140	-154.575	89.16364	74.07514	74.07514	-42.1865	29.19124
16	150	-152.738	92.7101	74.50568	74.50568	-40.0458	32.73771
17	160	-150.784	95.90968	75.46784	75.46784	-37.8385	35.93728
18	170	-148.726	98.72429	76.93494	76.93494	-35.6145	38.75189
19	180	-146.585	101.1197	78.8803	78.8803	-33.4153	41.1473
20	190	-144.385	103.0651	81.27571	81.27571	-31.2738	43.09266
21	200	-142.162	104.5322	84.09032	84.09032	-29.216	44.55977
22	210	-139.954	105.4943	87.2899	87.2899	-27.2616	45.52193
23	220	-137.813	105.9249	90.83636	90.83636	-25.4253	45.95246
24	230	-135.799	105.7953	94.68749	94.68749	-23.718	45.82295
25	240	-133.982	105.0738	98.79657	98.79657	-22.1481	45.10136
26	250	-132.442	103.7228	103.1118	103.1118	-20.7237	43.75041
27	260	-131.273	101.6989	107.5749	107.5749	-19.4536	41.72654
28	270	-130.578	98.95267	112.1192	112.1192	-18.3498	38.98027
29	280	-130.472	95.4317	116.6655	116.6655	-17.4304	35.4593
30	290	-131.072	91.08878	121.1163	121.1163	-16.7229	31.11638
31	300	-132.486	85.89789	125.3465	125.3465	-16.2692	25.9255
32	310	-134.794	79.88337	129.1894	129.1894	-16.133	19.91097
33	320	-138.007	73.16632	132.4176	132.4176	-16.4088	13.19392
34	330	-142.02	66.02657	134.7227	134.7227	-17.2304	6.054174
35	340	-146.563	58.95782	135.7099	135.7099	-18.7691	-1.01457
36	350	-151.197	52.65532	134.9507	134.9507	-21.1972	-7.31707
37	360	-155.409	47.85553	132.1445	132.1445	-24.5908	-12.1169

6.1.7 Results of Angular Velocity Analysis of right leg:

Table 6.5 Angular Velocity Analysis of right leg

SL NO	CRANK ANGLE(deg)	Link 3 (rad/s)	Link 4 (rad/s)	Link 5 (rad/s)	Link 6 (rad/s)	Link 7 (rad/s)	Link 8 (rad/s)
1	0	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512	-11.586
2	10	-8.73894	-5.26509	-16.9906	-16.9906	-13.5168	-5.28094
3	20	-5.87518	0.546654	-20.4398	-20.4398	-14.018	0.548299
4	30	-3.44833	5.15404	-21.6171	-21.6171	-13.0147	5.169549
5	40	-1.5686	8.476884	-20.9746	-20.9746	-10.9292	8.502391
6	50	-0.15301	10.73877	-19.1909	-19.1909	-8.29915	10.77109
7	60	0.923402	12.20605	-16.8389	-16.8389	-5.55625	12.24278
8	70	1.767533	13.09285	-14.2966	-14.2966	-2.97127	13.13224
9	80	2.457213	13.55014	-11.7754	-11.7754	-0.68243	13.59091
10	90	3.045643	13.67923	-9.37485	-9.37485	1.258737	13.72039
11	100	3.568034	13.54713	-7.12927	-7.12927	2.849825	13.5879
12	110	4.046858	13.19849	-5.03884	-5.03884	4.1128	13.23821
13	120	4.49535	12.66379	-3.08864	-3.08864	5.079794	12.70189
14	130	4.919673	11.96486	-1.25948	-1.25948	5.785712	12.00086
15	140	5.3202	11.11857	0.466455	0.466455	6.264823	11.15202
16	150	5.692273	10.13911	2.102629	2.102629	6.549462	10.16961
17	160	6.026708	9.039326	3.657079	3.657079	6.669697	9.066525
18	170	6.310215	7.831239	5.132296	5.132296	6.65332	7.854803
19	180	6.525822	6.525822	6.525822	6.525822	6.525822	6.545458
20	190	6.65332	5.132296	7.831239	7.831239	6.310215	5.14774
21	200	6.669697	3.657079	9.039326	9.039326	6.026708	3.668083
22	210	6.549462	2.102629	10.13911	10.13911	5.692273	2.108956
23	220	6.264823	0.466455	11.11857	11.11857	5.3202	0.467858
24	230	5.785712	-1.25948	11.96486	11.96486	4.919673	-1.26327
25	240	5.079794	-3.08864	12.66379	12.66379	4.49535	-3.09794
26	250	4.1128	-5.03884	13.19849	13.19849	4.046858	-5.054
27	260	2.849825	-7.12927	13.54713	13.54713	3.568034	-7.15073
28	270	1.258737	-9.37485	13.67923	13.67923	3.045643	-9.40306
29	280	-0.68243	-11.7754	13.55014	13.55014	2.457213	-11.8108
30	290	-2.97127	-14.2966	13.09285	13.09285	1.767533	-14.3396
31	300	-5.55625	-16.8389	12.20605	12.20605	0.923402	-16.8896
32	310	-8.29915	-19.1909	10.73877	10.73877	-0.15301	-19.2487
33	320	-10.9292	-20.9746	8.476884	8.476884	-1.5686	-21.0378
34	330	-13.0147	-21.6171	5.15404	5.15404	-3.44833	-21.6822
35	340	-14.018	-20.4398	0.546654	0.546654	-5.87518	-20.5013
36	350	-13.5168	-16.9906	-5.26509	-5.26509	-8.73894	-17.0418
37	360	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512	-11.586

6.1.8 Results of Angular Acceleration Analysis of right leg:

Table 6.6Angular Acceleration Analysis of right leg

SL NO	CRANK ANGLE(deg)	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8
1	0	434.3621	1048.79	-1048.79	-1049.39	-434.362	1051.386
2	10	507.9822	1071.723	-786	-786.119	-222.259	1074.839
3	20	462.4521	905.3876	-392.36	-392.361	50.57563	908.1109
4	30	369.3495	677.4411	-27.0232	-27.1129	281.0683	679.4153
5	40	279.6687	472.0226	227.5073	227.2902	419.8612	473.3216
6	50	210.7042	313.4152	369.0839	368.7617	471.7949	314.2365
7	60	162.4192	197.1399	428.7728	428.3745	463.4935	197.6585
8	70	129.9841	111.9979	439.3246	438.8725	421.3383	112.3349
9	80	108.6144	48.06421	424.6873	424.1973	364.1371	48.29456
10	90	94.66655	-1.80135	399.6565	399.1408	303.1885	-1.6356
11	100	85.5523	-42.3537	372.3618	371.8314	244.4558	-42.2327
12	110	79.4284	-76.6418	346.7337	346.1997	190.6634	-76.5611
13	120	74.92476	-106.561	324.2591	323.7343	142.7737	-106.526
14	130	70.95535	-133.237	305.08	304.5787	100.8881	-133.26
15	140	66.60077	-157.295	288.6405	288.1785	64.74515	-157.393
16	150	61.04418	-179.053	274.065	273.658	33.96768	-179.245
17	160	53.54429	-198.679	260.3851	260.0465	8.162237	-198.978
18	170	43.43081	-216.314	246.6838	246.4222	-13.0614	-216.73
19	180	30.10904	-232.188	232.1877	232.0041	-30.109	-232.72
20	190	13.06143	-246.684	216.3144	216.2021	-43.4308	-247.325
21	200	-8.16224	-260.385	198.6785	198.6231	-53.5443	-261.12
22	210	-33.9677	-274.065	179.0532	179.0357	-61.0442	-274.875
23	220	-64.7452	-288.641	157.2946	157.2938	-66.6008	-289.508
24	230	-100.888	-305.08	133.2366	133.231	-70.9554	-305.994
25	240	-142.774	-324.259	106.5606	106.5294	-74.9248	-325.214
26	250	-190.663	-346.734	76.64184	76.56402	-79.4284	-347.732
27	260	-244.456	-372.362	42.35366	42.20676	-85.5523	-373.413
28	270	-303.189	-399.656	1.801347	1.55916	-94.6666	-400.779
29	280	-364.137	-424.687	-48.0642	-48.4342	-108.614	-425.9
30	290	-421.338	-439.325	-111.998	-112.537	-129.984	-440.646
31	300	-463.494	-428.773	-197.14	-197.898	-162.419	-430.205
32	310	-471.795	-369.084	-313.415	-314.444	-210.704	-370.583
33	320	-419.861	-227.507	-472.023	-473.352	-279.669	-228.935
34	330	-281.068	27.02321	-677.441	-679.019	-369.349	25.97589
35	340	-50.5756	392.3599	-905.388	-906.995	-462.452	392.2013
36	350	222.2593	785.9999	-1071.72	-1072.97	-507.982	787.239
37	360	434.3621	1048.79	-1048.79	-1049.39	-434.362	1051.386

6.1.9 Graphs Ploted For The Crank Angle Vs Anglar Position,Velocity, And Acceleration of two legs:

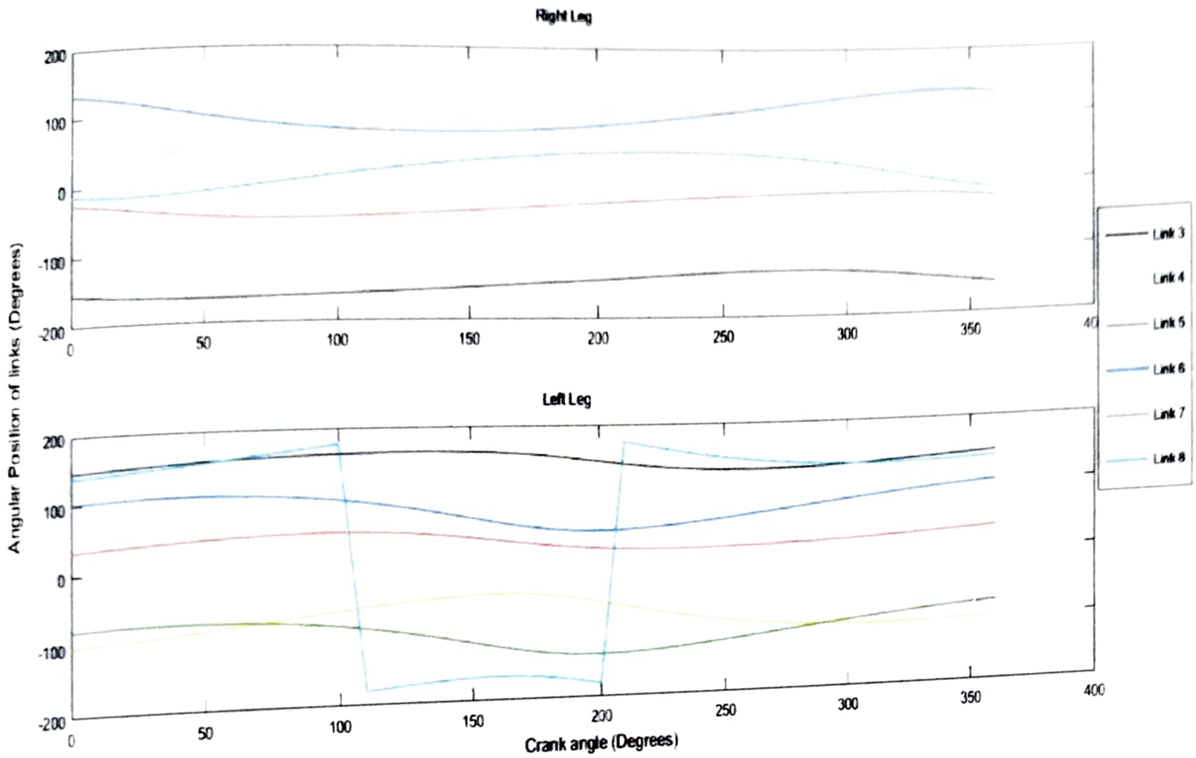


Figure 6.3 Crank Angle vs Angular position of right and left leg

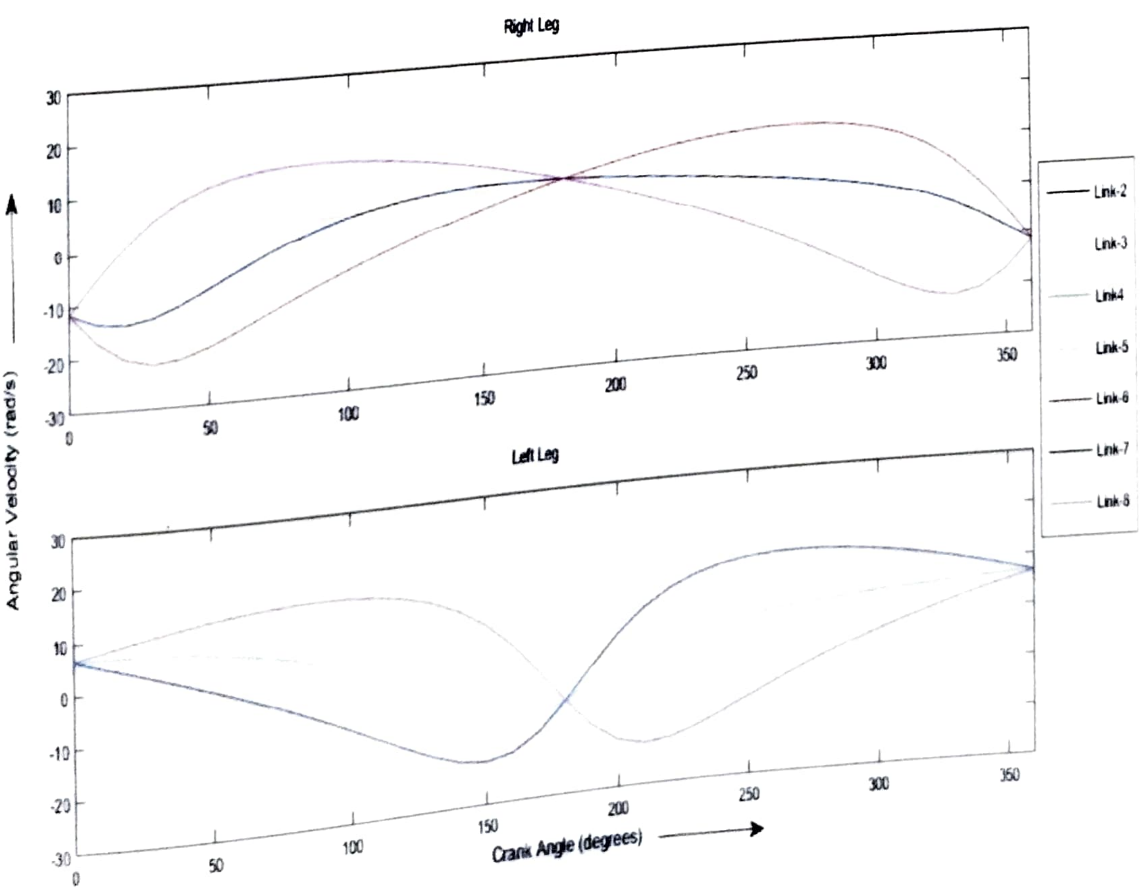


Figure 6.4 Crank Angle vs Angular Velocity of right and left leg

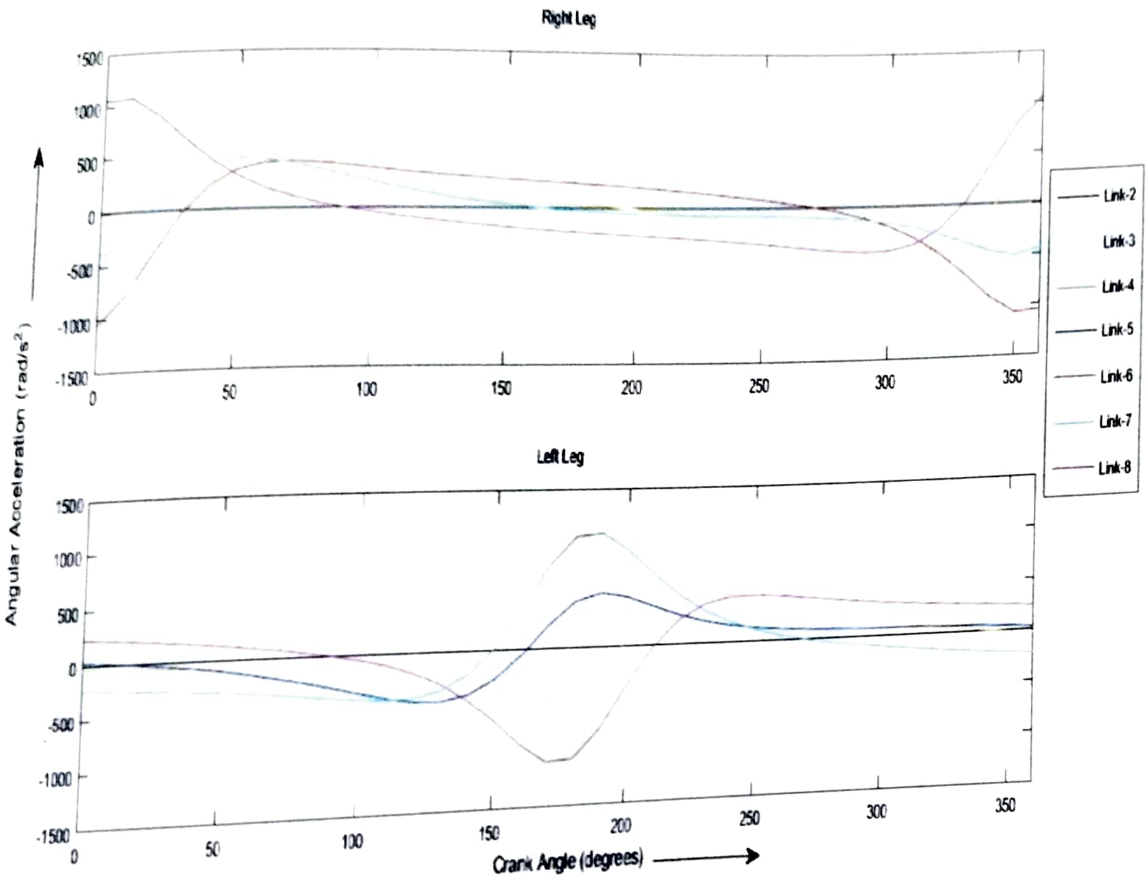


Figure 6.5 Crank Angle vs Angular acceleration of right and left leg

6.1.10 Variation of step length and step height by varying fixed link length and crank radius:

The variation of step length and step height of a foot point trajectory for a change in fixed link length and change in crank radius is presented. It can be observed that the step length varies linearly whereas the step height varies non-linearly. These results can be used in designing the leg mechanism for: (1) a desired range of speeds (depends on step length) and(2) a terrain with given maximum obstacle size (depends on step height).

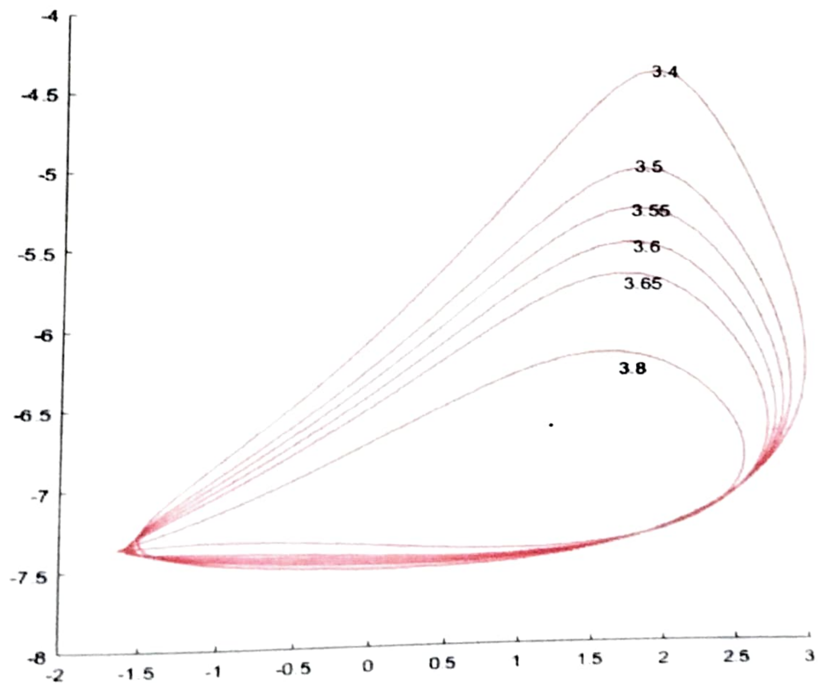
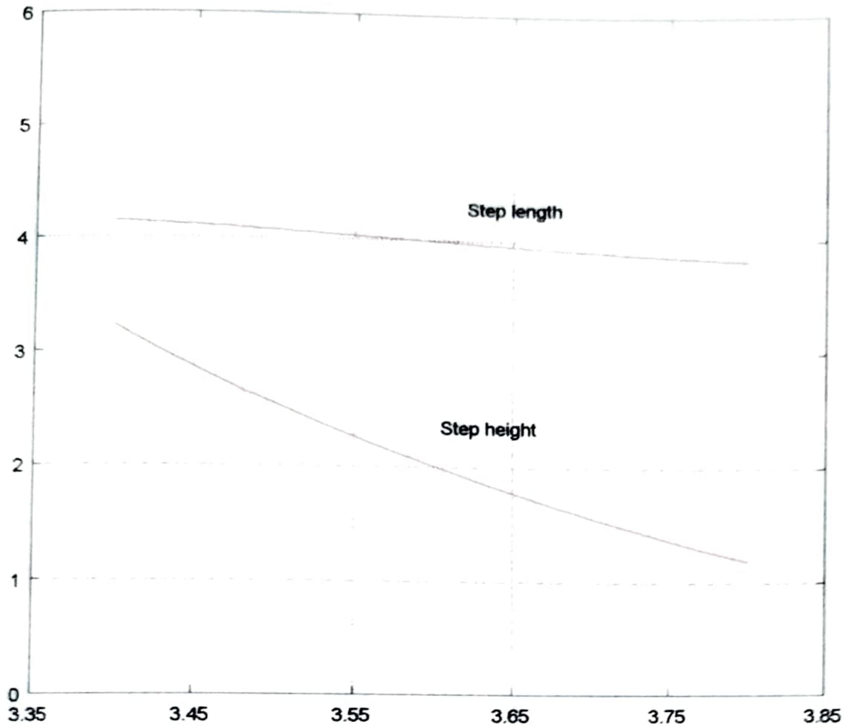


Figure-6.6. Change in step height and step length for varying fixed link length



ure-6.7. **Graph for change in step height and step length for varying fixed link length**

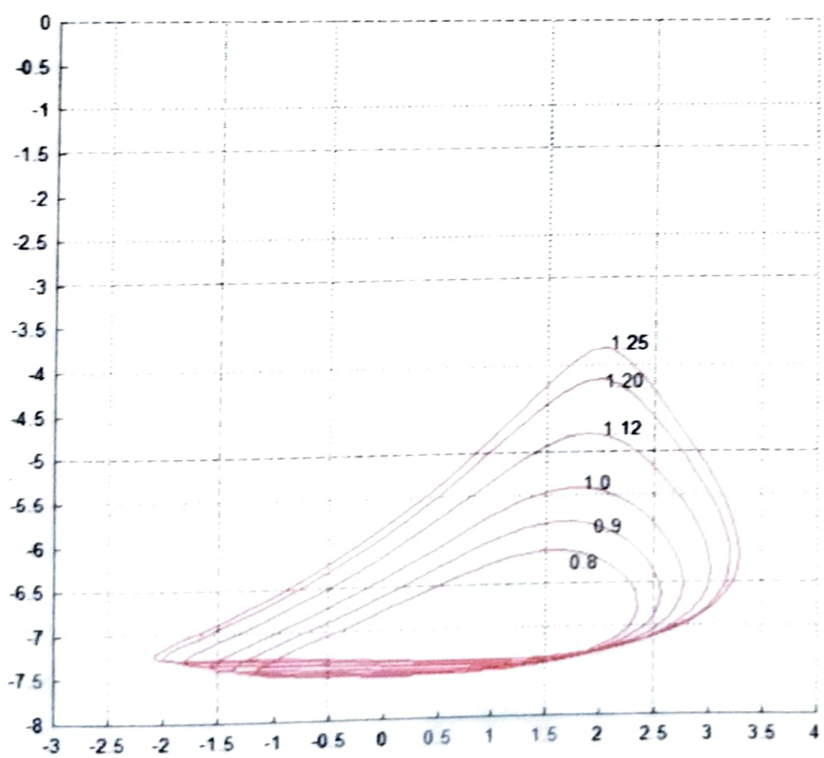


Figure-6.8. Change in step height and step length for varying crank radius

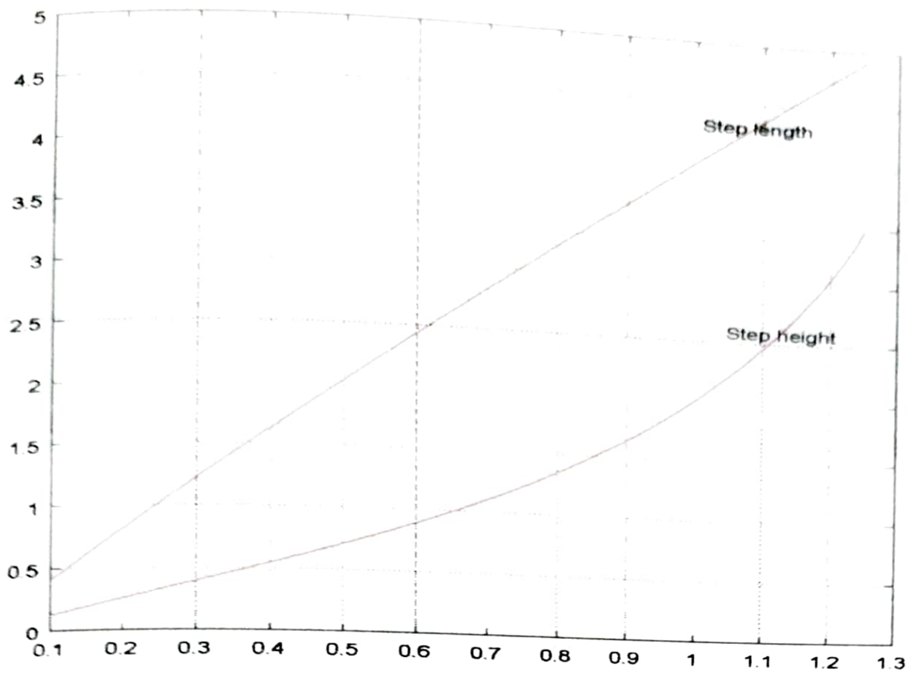


Figure-6.9. Graph for change in step height and step length for varying fixed link length

6.2VALIDATION:

6.2.1 GRAPHICAL APPROACH

For the comparison of analysis by analytical approach, graphical approach is presented for position, angular velocity and angular acceleration at $\theta_2=60^0$.

6.2.2 POSITION ANALYSIS OF LEFT LEG:

For input link 2, when, $\theta_2=60^0$, each link angle is measured and compared with the analytical values,

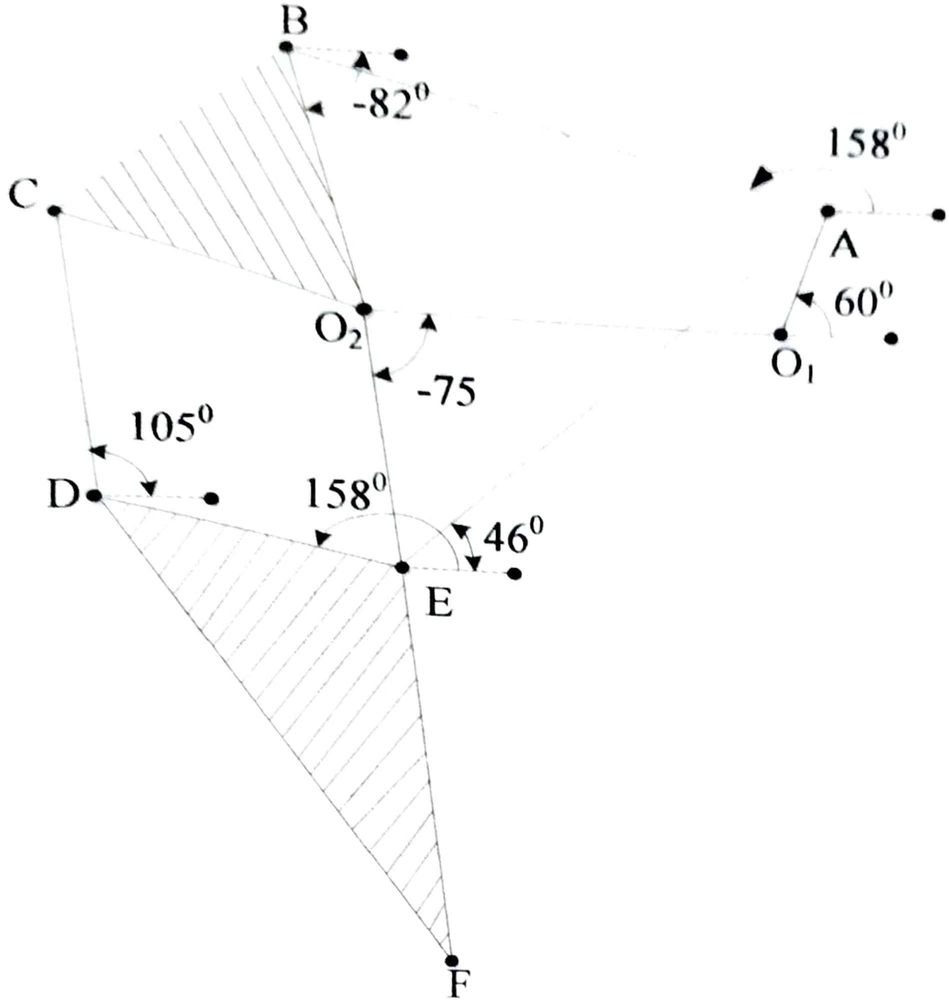


Figure 6.10 Link positions of two legged Theo-Jansen's Mechanism at $\theta_2=60^0$ for left leg

Table 6.7: Position analysis comparison for left leg θ(Graphical) (vs) θ (Analytical)

LINK NO	1	2	3	4	5	6	7	8
θ (Graphical)(deg)	0	60	158	-82	105	-75	46	158
θ (Analytical)(deg)	0	60	157.85	-81.2	105.25	-74.92	46.02	158.66

6.2.3 ANGULAR VELOCITY OF LEFT LEG: (ω)

By graphical approach: **(Anti-clock Wise Positive)**

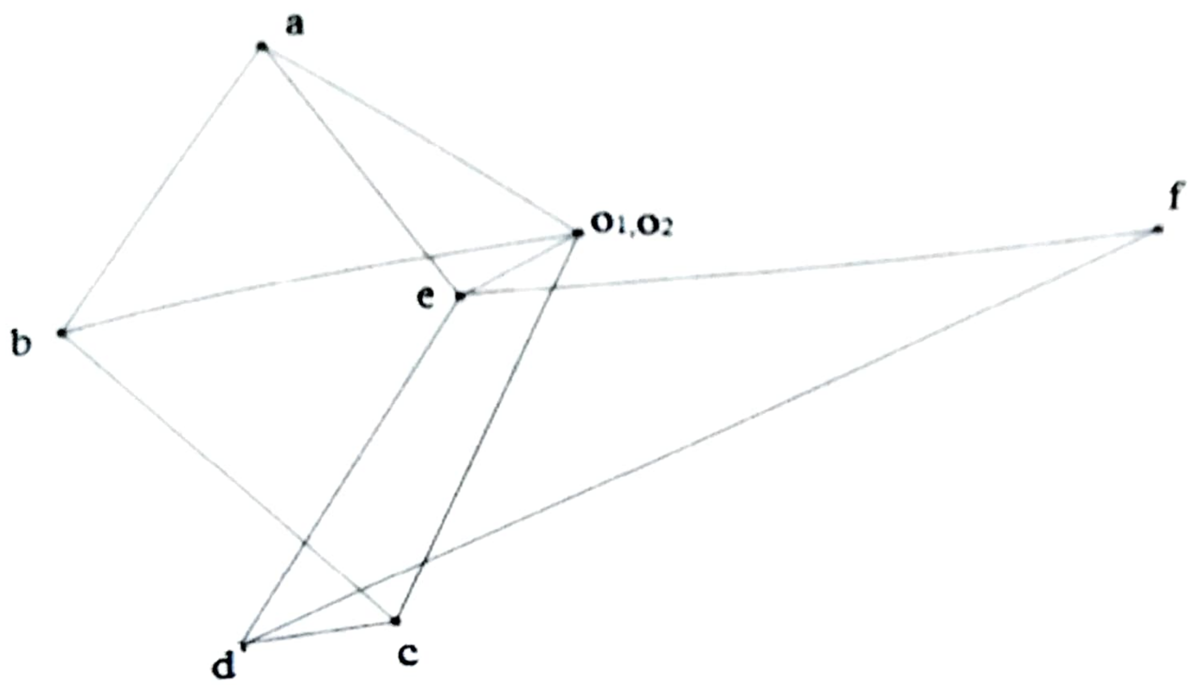


Figure 6.11 Velocity Diagram for left leg of Two-Legged Theo-Jansen's mechanism at $\theta_2=60^0$.

Scale = 1:10

o_1a=12.510, ae=10.292, cd=3.587,

ab=8.931, de=12.629, df=33.896,

bc=13.525, o_2e=3.565, o_2c=12.601,

o_2b=14.389, ef=25.527

$\omega_3 = \frac{V_{ba}}{BA}$=4.3934 rad/s, (in the same direction as ω_2)

$\omega_4 = \frac{V_{o_2b}}{O_2B}$ = 12.6112 rad/s (in the same direction as ω_2)

$\omega_5 = \frac{V_{eo_2}}{EO_2}$ = 3.1246 rad/s (in opposite direction of ω_2)

$\omega_6 = \frac{V_{ea}}{EA}$ = 5.0627 rad/s (in the same direction as ω_2)

$\omega_7 = \frac{V_{dc}}{DC}$ = 3.1440 rad/s (in opposite direction of ω_2)

$\omega_8 = \frac{V_{de}}{DE}$ = 12.6673 rad/s (in the same direction as ω_2)

Table 6.8: Velocity analysis comparison for left leg ω(Graphical) (vs) ω(Analytical)

LINK NO	1	2	3	4	5	6	7	8
ω (Graphical)(rad/s)	0	30	4.3934	12.6112	-3.1246	5.0627	-3.144	12.667
ω (Analytical)(rad/s)	0	30	4.495	12.66	-3.088	5.08	-3.12	12.73

6.2.4ANGULAR ACCELERATION OF LEFT LEG (α):

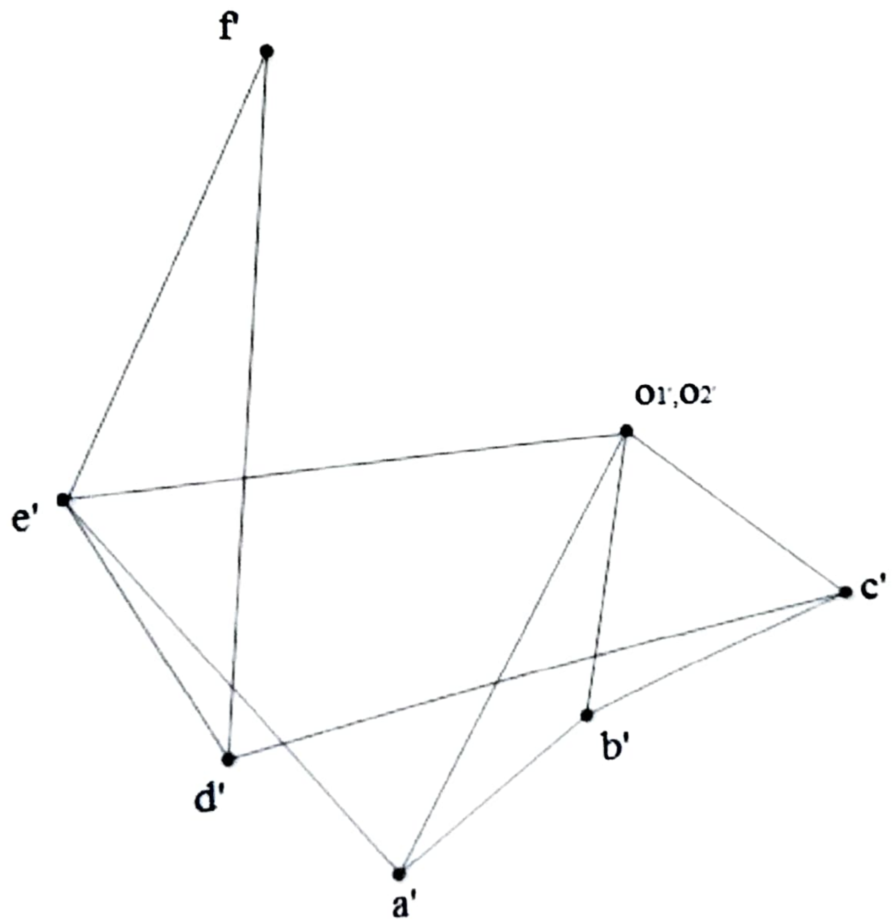


Figure 6.12 Acceleration Diagram for left leg of two legged Theo-Jansen's mechanism at $\theta_2=60^0$.

$$\alpha_3 = \frac{a^t_{a'b'}}{AB} = -76.76 \text{ rad/s}^2$$

$$\alpha_4 = \frac{a^t_{b'o_2'}}{BO_2} = 103.562 \text{ rad/s}^2$$

$$\alpha_5 = \frac{a^t_{e'o_2'}}{EO_2} = -325.15 \text{ rad/s}^2$$

$$\alpha_6 = \frac{a^t_{e'a'}}{EA} = -143.87 \text{ rad/s}^2$$

$$\alpha_7 = \frac{a^t_{d'c'}}{DC} = 325 \text{ rad/s}^2$$

$$\alpha_8 = \frac{a^t_{d'e'}}{DE} = 103.24 \text{ rad/s}^2$$

Table 6.9: Acceleration analysis comparison for left leg α(Graphical) (vs) α(Analytical)

LINK NO	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
α (Graphical) (rad/s^2)	0	0	-76.76	103.562	-325.15	-143.24	-325	103.26
α (Analytical) (rad/s^2)	0	0	-74.92	106.56	-324.26	-142.77	-323.71	107.05

6.2.5 POSITION ANALYSIS OF RIGHT LEG:

For input link 2, when, $\theta_2=60^0$, each link angle is measured and compared with the analytical values,

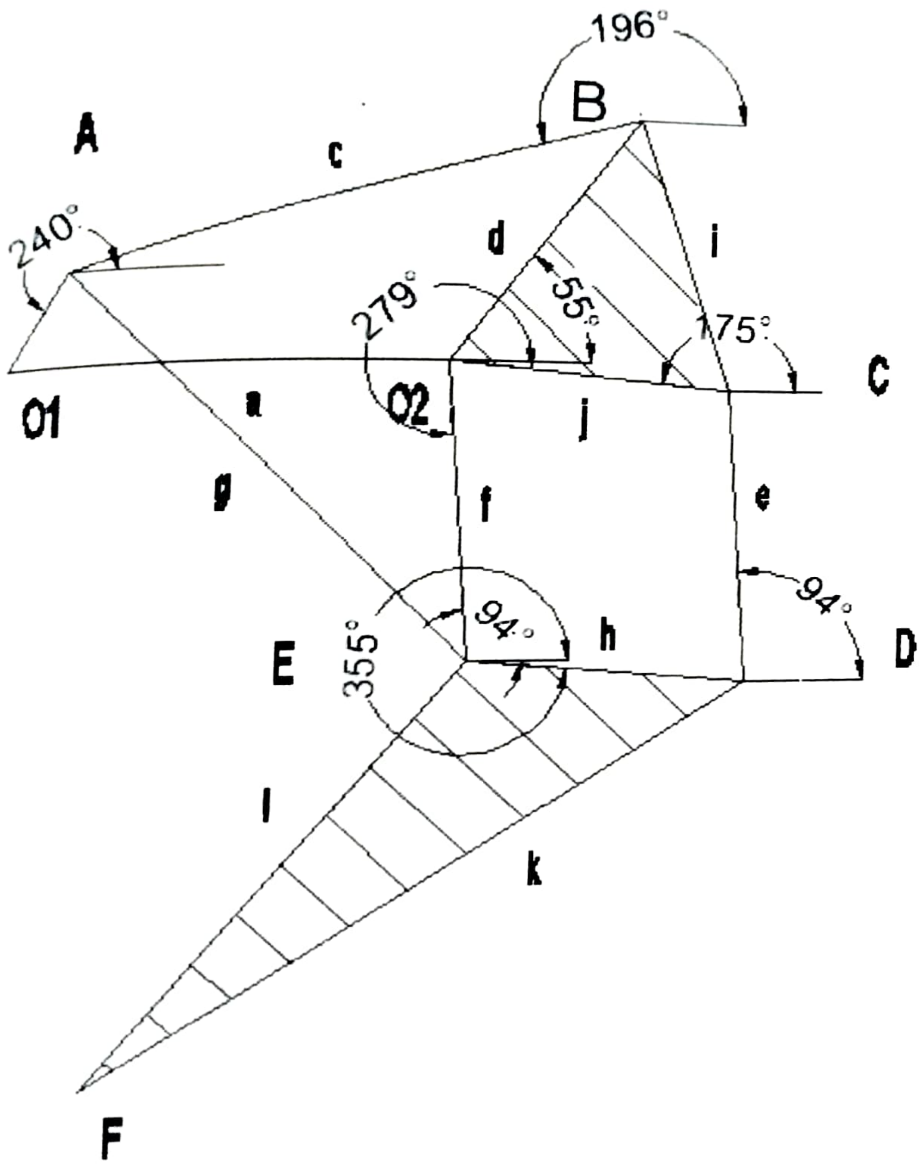


Figure 6.13 Link positions of two legged Theo-Jansen's Mechanism at $\theta_2=60^0$ for right leg

Table 6.10: Position analysis comparison for right leg θ (Graphical) (vs) θ (Analytical)

LINK NO	1	2	3	4	5	6	7	8
θ (Graphical)(deg)	0	60	196	55	94	94	312	355
θ (Analytical)(deg)	0	60	198	54.65	98.36	98.36	315.2	354.7

6.2.6 ANGULAR VELOCITY OF RIGHT LEG : (ω)

By graphical approach: **(Anti-clock Wise Positive)**

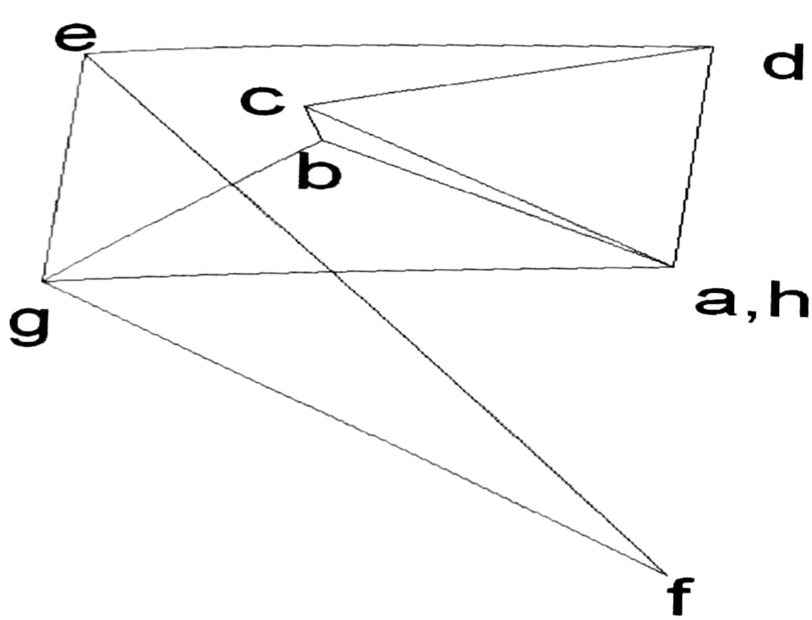


Figure 6.14 Velocity Diagram of right leg of two legged Theo-Jansen's mechanism at $\theta_2=60^0$.

ab=12.510, bc=0.1877, ch=1.3927,

gh=1.9213, de=1.9195, gb=1.1296, ge=1.2253

$$\omega_2 = \frac{V_{ba}}{ba} = 30\ rad/s$$

$$\omega_3 = \frac{V_{bc}}{BC} = 0.92\ rad/s, \text{ (in the same direction as } \omega_2 \text{)}$$

$$\omega_4 = \frac{V_{ch}}{CH} = 12.20\ rad/s, \text{ (in the same direction as } \omega_2 \text{)}$$

$\omega_5 = \frac{V_{gh}}{GH} = 16.83\ rad/s$,(in opposite direction of ω_2)

$\omega_6 = \frac{V_{de}}{DE} = 16.82\ rad/s$. (in opposite direction of ω_2)

$\omega_7 = \frac{V_{gb}}{GB} = 5.55\ rad/s$,(in opposite direction of ω_2)

$\omega_8 = \frac{V_{eg}}{EG} = 12.28\ rad/s$,(in the same direction as ω_2)

Table 6.11: Velocity analysis comparison ω(Graphical) (vs) ω(Analytical)

LINK NO	1	2	3	4	5	6	7	8
ω (Graphical)(rad/s)	0	30	0.92	12.20	-16.83	-16.82	-5.55	12.289
ω (Analytical)(rad/s)	0	30	0.923	12.20	-16.84	-16.84	-5.55	12.24

6.2.7 ANGULAR ACCELERATION OF RIGHT LEG (α):

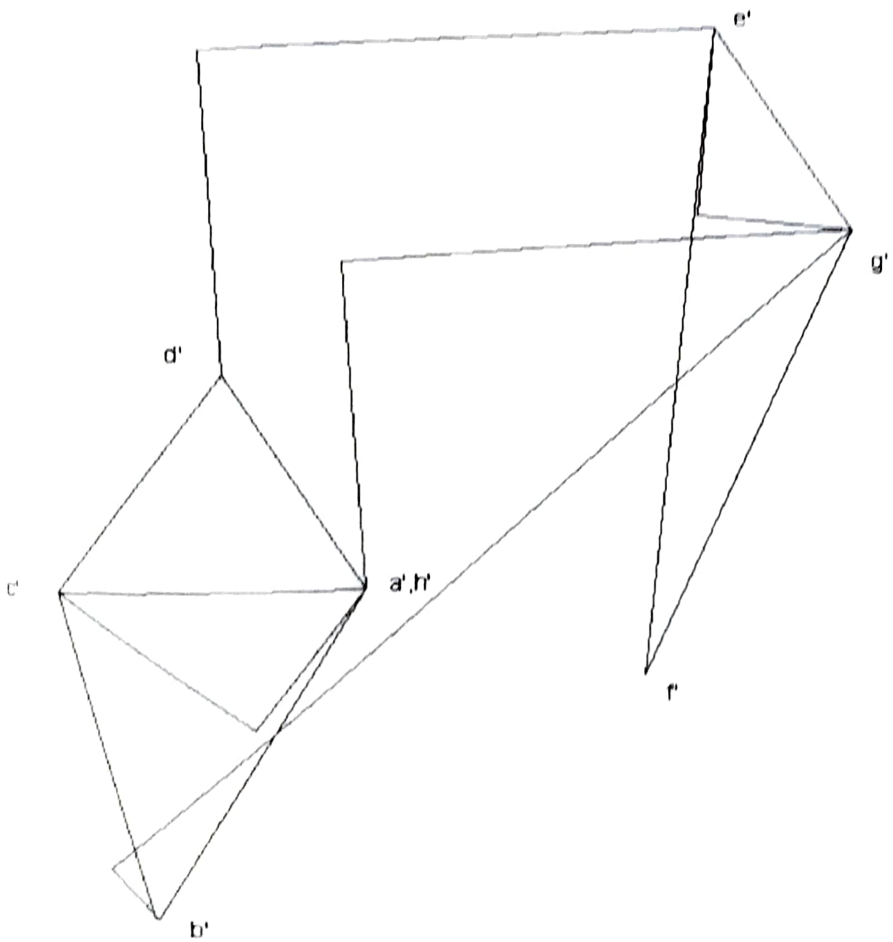


Figure 6.15 Acceleration Diagram for right leg of two legged Theo-Jansen's

mechanism at $\theta_2 = 60^0$.

$$\alpha_3 = \frac{a^t_{c'b'}}{CB} = 162.28\ rad/s^2$$

$$\alpha_4 = \frac{a^t_{c'h'}}{CH} = 196.99\ rad/s^2$$

$$\alpha_5 = \frac{a^t_{g'h'}}{GH} = 428.71\ rad/s^2$$

$$\alpha_6 = \frac{a^t_{c'd'}}{CB} = 426.48\ rad/s^2$$

$$\alpha_7 = \frac{a^t_{g'b'}}{GB} = 463.40\ rad/s^2$$

$$\alpha_8 = \frac{a^t_{e'g'}}{EG} = 195.28\ rad/s^2$$

Table 6.12: Acceleration analysis comparison α(Graphical) (vs) α(Analytical)

LINK NO	1	2	3	4	5	6	7	8
α (Graphical) (rad/s^2)	0	0	162.28	196.99	428.71	426.48	463.4	195.28
α (Analytical) (rad/s^2)	0	0	162.42	197.1	428.8	428.4	463.5	197.7

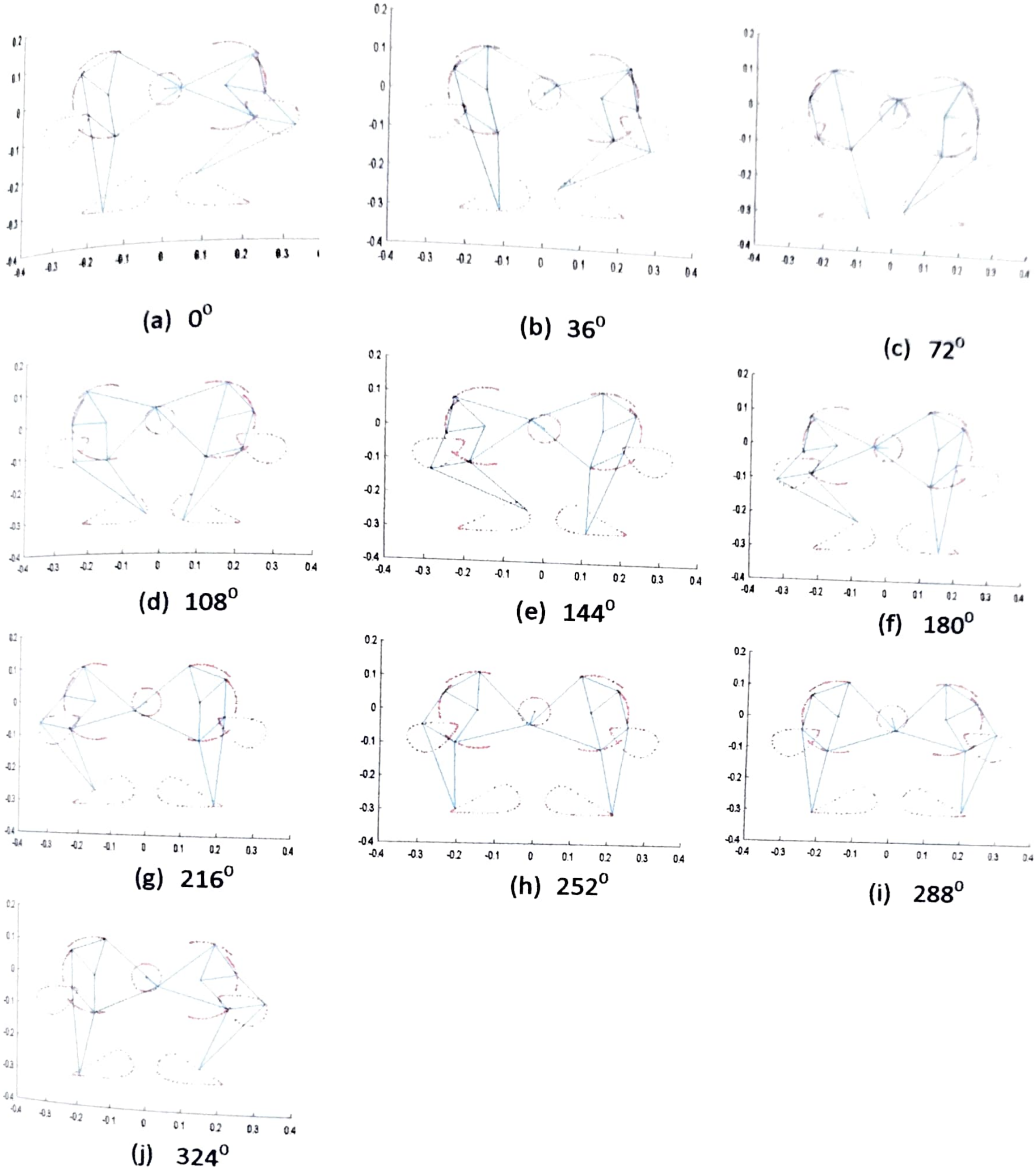


Figure 6.16 Configuration of Jansen leg mechanisms at various crank angles. Trajectories of all the joints including the foot point are also marked.

CHAPTER 7

7. CONCLUSIONS

- In this project kinematic analysis and simulation of Two-Legged Theo-Jansen's mechanism is performed.
- Equations are derived for position, angular velocity and angular acceleration of every link of Jansen's linkage using complex Algebraic method and the results are validated with the graphical method for a crank angle of 60°. The validation showed that the errors are within the desirable limits of 10%.
- The angular displacement, angular velocity and angular acceleration are evaluated and plotted for all the links of the mechanism for one complete cycle of input link.
- The path of every joint is plotted for different crank position.
- Step height and step length is measured and plotted for varying fixed link lengths and also for varying crank radius.

CHAPTER 8

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CHAPTER 9

APPENDIX

Math lab programme for solving kinematic analysis and simulation of two leg Jansen's mechanism:

```
clc;
clear all;
a=0.15;
b=.0417;
c=0.2033;
d=0.1141;
e=0.1141;
f=0.1141;
g=0.2033;
h=0.0997;
i=0.1077;
j=0.10;
k=0.268;
l=0.20;
prompt = {'Enter the number of revolutions   :','Enter the angular
speed of crank   :'};

dlg_title = 'inputs';
num_lines = 1;
def = {'20','20'};
link = inputdlg(prompt,dlg_title,num_lines,def);

n=str2num(link{1});
ang1=n*360;

ang_speed=str2num(link{2});
tetalh=acosd((l^2+h^2-k^2)/(2*l*h));
tetakh=acosd((k^2+h^2-l^2)/(2*k*h));
tetaid=acosd((i^2+d^2-j^2)/(2*i*d));
tetaij=acosd((i^2+j^2-d^2)/(2*i*j));

ang=0:10:ang1;

theta21=ang;
theta1=0*ang;

    theta2=180.+theta21;
%Position Analysis
%First loop
k1=a/c;
k2=a/b;
k3=(d^2-c^2-a^2-b^2)/(2*b*c);
A=k3+cosd(theta2)+k2-(k1*cosd(theta2));
B=-2*sind(theta2);
C=k3-cosd(theta2)-k2-(k1*cosd(theta2));
theta31=2.*atand((-B+sqrt((B.^2)-(4.*A.*C)))./(2.*A));
theta32=2.*atand((-B-sqrt((B.^2)-(4.*A.*C)))./(2.*A));
k4=a/d;
k5=a/b;
k6=(c^2-a^2-b^2-d^2)/(2*b*d);
D=k6-(k4*cosd(theta2))+k5+cosd(theta2);
E=-2*sind(theta2);
```

```
F=k6-(k4*cosd(theta2))-k5-cosd(theta2);
theta41=2.*atand((-E+(sqrt(E.^2-(4.*D.*F)))))./(2.*D));
theta42=2.*atand((-E-(sqrt(E.^2-(4.*D.*F)))))./(2.*D));
%Second loop
M1=(c*cosd(theta32))+(d*cosd(theta41));
M2=(c*sind(theta32))+(d*sind(theta41));
p1=(((g^2)-(M1.^2)-(M2.^2)-(f^2))/(2*f));
G=p1+M1;
H=-2*M2;
I=p1-M1;
theta51=2.*(atand((-H+(sqrt(H.^2-(4.*I.*G)))))./(2.*G)));
theta52=2.*(atand((-H-(sqrt(H.^2-(4.*I.*G)))))./(2.*G)));
p2=(f^2-M1.^2-M2.^2-g^2)/(2*g);
J=p2+M1;
K=-2*M2;
L=p2-M1;
theta71=2.*atand((-K+(sqrt(K.^2-(4.*J.*L)))))./(2.*J));
theta72=2.*atand((-K-(sqrt(K.^2-(4.*J.*L)))))./(2.*J));
%Third loop
theta10=180+theta52;
tetadj=acosd((d^2+j^2-i^2)/(2*j*d));
theta9=180+(theta41-tetadj);
N1=(h*cosd(theta9))+(e*cosd(theta10));
N2=(h*sind(theta9))+(e*sind(theta10));
q1=((e^2)-(h^2)-(N1.^2)-(N2.^2))./(2*h);
J=q1+N1;
K=(-2*N2);
L=q1-N1;
theta81=2.*atand((-K+(sqrt(K.^2-(4.*J.*L)))))./(2.*J));
theta82=2.*atand((-K-(sqrt(K.^2-(4.*J.*L)))))./(2.*J));
q2=((h^2)-(e^2)-(N1.^2)-(N2.^2))./(2*e);
X=q2+N1;
Y=(-2*N2);
Z=q2-N1;
theta61=2.*atand((-Y+(sqrt(Y.^2-(4.*X.*Z)))))./(2.*X));
theta62=2.*atand((-Y-(sqrt(Y.^2-(4.*X.*Z)))))./(2.*X));
%velocity analysis
omega1=0*ang;
omega2=30.+omega1;%input here
omega3=(b.*omega2.*sind(theta2-theta41))./(c.*sind(theta41-theta32));
omega4=(b.*omega2.*sind(theta2-theta32))./(d.*sind(theta32-theta41));
omega9=omega4;
omega5=((c.*omega3.*sind(theta32-theta71))+(d.*omega4.*sind(theta41-
theta71)))./(f.*sind(theta71-theta52));
omega10=omega5;

omega7=((c.*omega3.*sind(theta32-theta52))+(d.*omega4.*sind(theta41-
theta52)))./(g.*sind(theta52-theta71));
s1=(j.*omega9.*cosd(theta9))+(f.*omega10.*cosd(theta10));
s2=(j.*omega9.*sind(theta9))+(f.*omega10.*sind(theta10));
omega6=((s1.*sind(theta81))-(s2.*cosd(theta81)))./(e.*sind(theta62-
theta81));
omega8=((s1.*sind(theta62))-(s2.*cosd(theta62)))./(h.*sind(theta81-
theta62));
%acceleration analysis
alpha1=0*ang;
alpha2=0*ang;%input here
y1=(a.*alpha1.*cosd(theta1))+(b.*alpha2.*cosd(theta2))-
(a.*(omega1.^2).*sind(theta1))-(b.*(omega2.^2).*sind(theta2))-
(c.*(omega3.^2).*sind(theta32))-(d.*(omega4.^2).*sind(theta41));
```

```
y2=(a.*alpha1.*sind(theta1))+(b.*alpha2.*sind(theta2))+(a.*(omega1.^2
).*cosd(theta1))+(b.*(omega2.^2).*cosd(theta2))+(c.*(omega3.^2).*cosd
(theta32))+(d.*(omega4.^2).*cosd(theta41));


alpha3=((y1.*sind(theta41))-(y2.*cosd(theta41)))./(c*sind(theta32-
theta41));
alpha4=((y1.*sind(theta32))-(y2.*cosd(theta32)))./(d*sind(theta41-
theta32));

x1=(c.*alpha3.*cosd(theta32))-
(c.*(omega3.^2).*sind(theta32))+(d.*alpha4.*cosd(theta41))-
(d.*(omega4.^2).*sind(theta41))-(g.*(omega7.^2).*sind(theta71))-
(f.*(omega5.^2).*sind(theta52));
x2=(c.*alpha3.*sind(theta32))+(c.*(omega3.^2).*cosd(theta32))+(d.*alp
ha4.*sind(theta41))+(d.*(omega4.^2).*cosd(theta41))+(g.*(omega7.^2).*
cosd(theta71))+(f.*(omega5.^2).*cosd(theta52));

alpha5=((x2.*cosd(theta71))-(x1.*sind(theta71)))./(f*sind(theta71-
theta52));
alpha7=((x2.*cosd(theta52))-(x1.*sind(theta52)))./(g*sind(theta52-
theta71));
alpha10=alpha5;alpha9=alpha4;

z1=(j.*alpha9.*cosd(theta9))-
(j.*(omega9.^2).*sind(theta9))+(f.*alpha10.*cosd(theta10))-
(f.*(omega10.^2).*sind(theta10))-(h.*(omega8.^2).*sind(theta81))-
(e.*(omega6.^2).*sind(theta62));
z2=(j.*alpha9.*sind(theta9))+(j.*(omega9.^2).*cosd(theta9))+(f.*alpha
10.*sind(theta10))+(f.*(omega10.^2).*cosd(theta10))+(h.*(omega8.^2).*
cosd(theta81))+(e.*(omega6.^2).*cosd(theta62));
alpha6=((z1.*sind(theta81))-(z2.*cosd(theta81)))./(e.*sind(theta62-
theta81));
alpha8=((z1.*sind(theta62))-(z2.*cosd(theta62)))./(h.*sind(theta81-
theta62));



P1=[0;0];
P2=b*[cosd(theta2-180);sind(theta2-180)];
P3=P2+c*[cosd(theta32-180);sind(theta32-180)];
P4=P3+i*[cosd(180+tetaid+theta41);sind(180+tetaid+theta41)];
P5=P4+e*[cosd(180+theta62);sind(180+theta62)];
P6=[b*cosd(theta2-180)+g*cosd(theta71)+l*cosd(360-(tetalh-
theta81));b*sind(theta2-180)+g*sind(theta71)+l*sind(360-(tetalh-
theta81))];

P7=[b*cosd(theta2-180)+g*cosd(theta71);b*sind(theta2-
180)+g*sind(theta71)];
 P8=a*[1;0];
btech2018twolegslef;
for i=1:length(ang);
    P1_circle=viscircles(P1',0.0005);
    P2_circle=viscircles(P2(:,i)',0.0005);
    P3_circle=viscircles(P3(:,i)',0.0005);
    P4_circle=viscircles(P4(:,i)',0.0005);
    P5_circle=viscircles(P5(:,i)',0.0005);
    P6_circle=viscircles(P6(:,i)',0.0005);
    P7_circle=viscircles(P7(:,i)',0.0005);
    P8_circle=viscircles(P8',0.0005);
    P9_circle=viscircles(P9(:,i)',0.0005);
```

```
P10_circle=viscircles(P10(:,i)',0.0005);
P11_circle=viscircles(P11(:,i)',0.0005);
P12_circle=viscircles(P12(:,i)',0.0005);
P13_circle=viscircles(P13(:,i)',0.0005);
P14_circle=viscircles(P14(:,i)',0.0005);

B_bar= line([P1(1) P2(1,i)],[P1(2) P2(2,i)]);
C_bar= line([P2(1,i) P3(1,i)],[P2(2,i) P3(2,i)]);
D_bar= line([P3(1,i) P8(1)],[P3(2,i) P8(2)]);
I_bar= line([P3(1,i) P4(1,i)],[P3(2,i) P4(2,i)]);
J_bar= line([P4(1,i) P8(1)],[P4(2,i) P8(2)]);
E_bar= line([P4(1,i) P5(1,i)],[P4(2,i) P5(2,i)]);
H_bar= line([P5(1,i) P7(1,i)],[P5(2,i) P7(2,i)]);
K_bar= line([P5(1,i) P6(1,i)],[P5(2,i) P6(2,i)]);
L_bar= line([P6(1,i) P7(1,i)],[P6(2,i) P7(2,i)]);
G_bar= line([P7(1,i) P2(1,i)],[P7(2,i) P2(2,i)]);
F_bar= line([P7(1,i) P8(1)],[P7(2,i) P8(2)]);


C1_bar= line([P2(1,i) P9(1,i)],[P2(2,i) P9(2,i)]);
D1_bar= line([P9(1,i) P14(1,i)],[P9(2,i) P14(2,i)]);
I1_bar= line([P9(1,i) P10(1,i)],[P9(2,i) P10(2,i)]);
J1_bar= line([P10(1,i) P14(1,i)],[P10(2,i) P14(2,i)]);
E1_bar= line([P10(1,i) P11(1,i)],[P10(2,i) P11(2,i)]);
H1_bar= line([P11(1,i) P13(1,i)],[P11(2,i) P13(2,i)]);
K1_bar= line([P11(1,i) P12(1,i)],[P11(2,i) P12(2,i)]);
L1_bar= line([P12(1,i) P13(1,i)],[P12(2,i) P13(2,i)]);
G1_bar= line([P13(1,i) P2(1,i)],[P13(2,i) P2(2,i)]);
F1_bar= line([P13(1,i) P14(1,i)],[P13(2,i) P14(2,i)]);


  pause
if i<=length(ang)

      delete(B_bar);
      delete(C_bar);
      delete(D_bar);
      delete(E_bar);
      delete(F_bar);
      delete(G_bar);
      delete(H_bar);
      delete(I_bar);
      delete(J_bar);
      delete(K_bar);
      delete(L_bar);

      delete(C1_bar);
      delete(D1_bar);
      delete(E1_bar);
      delete(F1_bar);
      delete(G1_bar);
      delete(H1_bar);
      delete(I1_bar);
      delete(J1_bar);
      delete(K1_bar);
      delete(L1_bar);
```

```
end
end


figure(2)
angvelr=subplot(2,1,1);
plot(angvelr,theta21,omega2,'k',theta21,omega3,'y',theta21,omega4,'g'
,theta21,omega5,'c',theta21,omega6,'r',theta21,omega7,'b',theta21,ome
ga8,'m');
angvell=subplot(2,1,2);
plot(angvell,theta21,omega21,'k',theta21,omega31,'y',theta21,omega41,
'g',theta21,omega71,'c',theta21,omega61,'r',theta21,omega51,'b',theta
21,omega81,'m');


figure(3)
angaccr=subplot(2,1,1)
plot(angaccr,theta21,alpha2,'k',theta21,alpha3,'y',theta21,alpha4,'g'
,theta21,alpha5,'b',theta21,alpha6,'r',theta21,alpha7,'c',theta21,alp
ha8,'m');
angaccl=subplot(2,1,2)
plot(angaccl,theta21,alpha21,'k',theta21,alpha31,'y',theta21,alpha41,
'g',theta21,alpha71,'b',theta21,alpha61,'r',theta21,alpha51,'c',theta
21,alpha81,'m');


figure(4)
angpos=subplot(2,1,1)
plot(angpos,theta21,theta32,'k',theta21,theta41,'y',theta21,theta52,'
g',theta21,theta62,'b',theta21,theta71,'r',theta21,theta81,'c');
angposl=subplot(2,1,2)
plot(angposl,theta21,theta311,'k',theta21,theta421,'y',theta21,theta6
11,'g',theta21,theta511,'b',theta21,theta721,'r',theta21,theta821,'c'
);
```

%PROGRAMME FOR LEFT LEG(btech2018twolegslef)

```
theta21=theta21;
k1=a/c;
k2=a/b;
k3=(d^2-c^2-a^2-b^2)/(2*b*c);
A=k3+cosd(theta21)+k2-(k1*cosd(theta21));
B=-2*sind(theta21);
C=k3-cosd(theta21)-k2-(k1*cosd(theta21));
theta311=2.*atand((-B+sqrt((B.^2)-(4.*A.*C)))./(2.*A));
theta321=2.*atand((-B-sqrt((B.^2)-(4.*A.*C)))./(2.*A));
k4=a/d;
k5=a/b;
k6=(c^2-a^2-b^2-d^2)/(2*b*d);
D=k6-(k4*cosd(theta21))+k5+cosd(theta21);
E=-2*sind(theta21);
F=k6-(k4*cosd(theta21))-k5-cosd(theta21);
theta411=2.*atand((-E+(sqrt(E.^2-(4.*D.*F))))./(2.*D));
theta421=2.*atand((-E-(sqrt(E.^2-(4.*D.*F))))./(2.*D));
%Second loop
M1=(c*cosd(theta311))+(d*cosd(theta421));
M2=(c*sind(theta311))+(d*sind(theta421));
p1=(((g^2)-(M1.^2)-(M2.^2)-(f^2))/(2*f));
```

```
G=p1+M1;
H=-2*M2;
I=p1-M1;
theta611=2.*(atand((-H+(sqrt(H.^2-(4.*I.*G))))./(2.*G)));
theta621=2.*(atand((-H-(sqrt(H.^2-(4.*I.*G))))./(2.*G)));
p2=(f^2-M1.^2-M2.^2-g^2)/(2*g);
J=p2+M1;
K=-2*M2;
L=p2-M1;
theta711=2.*atand((-K+(sqrt(K.^2-(4.*J.*L))))./(2.*J));
theta721=2.*atand((-K-(sqrt(K.^2-(4.*J.*L))))./(2.*J));
theta101=360-(tetaij-((360+theta421)-tetaid-180));

N1=(j*cosd(theta101))+(f*cosd(theta611));
N2=(j*sind(theta101))+(f*sind(theta611));
q1=((e^2)-(h^2)-(N1.^2)-(N2.^2))./(2*h);
J=q1+N1;
K=(-2*N2);
L=q1-N1;
theta811=2.*atand((-K+(sqrt(K.^2-(4.*J.*L))))./(2.*J));
theta821=2.*atand((-K-(sqrt(K.^2-(4.*J.*L))))./(2.*J));
q2=((h^2)-(e^2)-(N1.^2)-(N2.^2))./(2*e);
X=q2+N1;
Y=(-2*N2);
Z=q2-N1;
theta511=2.*atand((-Y+(sqrt(Y.^2-(4.*X.*Z))))./(2.*X));
theta521=2.*atand((-Y-(sqrt(Y.^2-(4.*X.*Z))))./(2.*X));


omega11=0*ang;
omega21=30.+omega11;%input here
omega31=(b.*omega21.*sind(theta21-theta421))./(c.*sind(theta421-
theta311));
omega41=(b.*omega21.*sind(theta21-theta311))./(d.*sind(theta311-
theta421));
omega101=omega41;
omega91=omega41;
omega61=((c.*omega31.*sind(theta311-
theta721))+(d.*omega41.*sind(theta421-theta721)))./(f.*sind(theta721-
theta611));

s1=(j.*omega101.*sind(theta101))+(f.*omega61.*sind(theta611));
s2=(j.*omega101.*cosd(theta101))+(f.*omega61.*cosd(theta611));
omega51=((s1.*cosd(theta821))-
(s2.*sind(theta821)))./(e.*sind(theta821-theta511));
omega81=((s1.*cosd(theta511))-
(s2.*sind(theta511)))./(h.*sind(theta511-theta821));

omega71=((c.*omega31.*sind(theta311-
theta611))+(d.*omega41.*sind(theta421-theta611)))./(g.*sind(theta611-
theta721));

alpha11=0*ang;
alpha21=0*ang;%input here
y1=(a.*alpha11.*cosd(theta1))+(b.*alpha21.*cosd(theta21))-
(a.*(omega11.^2).*sind(theta1))-(b.*(omega21.^2).*sind(theta21))-
(c.*(omega31.^2).*sind(theta311))-(d.*(omega41.^2).*sind(theta421));
y2=(a.*alpha11.*sind(theta1))+(b.*alpha21.*sind(theta21))+(a.*(omega1
1.^2).*cosd(theta1))+(b.*(omega21.^2).*cosd(theta21))+(c.*(omega31.^2
).*cosd(theta311))+(d.*(omega41.^2).*cosd(theta421));
```

```
alpha31=((y1.*sind(theta421))-
(y2.*cosd(theta421)))./(c*sind(theta311-theta421));
alpha41=((y1.*sind(theta311))-
(y2.*cosd(theta311)))./(d*sind(theta421-theta311));
alpha101=alpha41;

x1=(c.*alpha31.*cosd(theta311))-
(c.*(omega31.^2).*sind(theta311))+(d.*alpha41.*cosd(theta421))-
(d.*(omega41.^2).*sind(theta421))-(g.*(omega71.^2).*sind(theta721))-
(f.*(omega61.^2).*sind(theta611));
x2=(c.*alpha31.*sind(theta311))+(c.*(omega31.^2).*cosd(theta311))+(d.
*alpha41.*sind(theta421))+(d.*(omega41.^2).*cosd(theta421))+(g.*(omeg
a71.^2).*cosd(theta721))+(f.*(omega61.^2).*cosd(theta611));

alpha61=((x2.*cosd(theta721))-
(x1.*sind(theta721)))./(f*sind(theta721-theta611));
alpha71=((x2.*cosd(theta611))-
(x1.*sind(theta611)))./(g*sind(theta611-theta721));

X3=(j.*alpha101.*sind(theta101))+(j.*(omega101.^2).*cosd(theta101))+(
e.*(omega51.^2).*cosd(theta511))+(h.*(omega81.^2).*cosd(theta821))+(f
.*alpha61.*sind(theta611))+(f.*(omega61.^2).*cosd(theta611));
X4=(j.*alpha101.*cosd(theta101))-(j.*(omega101.^2).*sind(theta101))-
(e.*(omega51.^2).*sind(theta511))-
(h.*(omega81.^2).*sind(theta821))+(f.*alpha61.*cosd(theta611))-
(f.*(omega61.^2).*sind(theta611));
alpha51=((X4.*sind(theta821))-
(X3.*cosd(theta821)))./(e.*sind(theta511-theta821));
alpha81=((X4.*sind(theta511))-
(X3.*cosd(theta511)))./(h.*sind(theta821-theta511));


P14=-a*[cosd(theta1);sind(theta1)];
P9=P2+c*[cosd(theta311);sind(theta311)];
P10=P9+i*[cosd(360-tetaid+theta421);sind(360-tetaid+theta421)];
P11=P10+e*[cosd(180+theta511);sind(180+theta511)];
P12=P11+[k*cosd(theta821+(180-tetakh));k*sind(theta821+(180-
tetakh))];
P13=P14+[f*cosd(theta611);f*sind(theta611)];
```

PROGRAMME FOR VARYING FIXED LINK TO PLOT STEP HEIGHT AND STEP LENGTH

```
%Link lengths

b=1;
c=4.87;
i=2.58;
e=2.74;
k=6.43;
l=4.80;
g=4.88;
h=2.39;
f=2.74;
d=2.74;
j=2.40;

cr=1;
for a=3.4:.01:3.8
```

```
p=1;
for theta2=0:5:360

k1=a/c;k2=a/b;k3=(d^2-c^2-a^2-b^2)/(2*b*c);
A=k3+cosd(theta2)+k2-(k1*cosd(theta2));
B=-2*sind(theta2);
C=k3-cosd(theta2)-k2-(k1*cosd(theta2));
theta31=2*atand((-B+sqrt((B^2)-(4*A*C)))/(2*A));
theta32=2*atand((-B-sqrt((b^2)-(4*A*C)))/(2*A));
k4=a/d;
k5=a/b;
k6=(c^2-a^2-b^2-d^2)/(2*b*d);
D=k6-(k4*cosd(theta2))+k5+cosd(theta2);
E=-2*sind(theta2);
F=k6-(k4*cosd(theta2))-k5-cosd(theta2);
theta41=2*atand((-E+(sqrt(E^2-(4*D*F))))/(2*D));
theta42=2*atand((-E-(sqrt(E^2-(4*D*F))))/(2*D));
%Second loop
M1=(c*cosd(theta31))+(d*cosd(theta42));
M2=(c*sind(theta31))+(d*sind(theta42));
p1=(((g^2)-(M1^2)-(M2^2)-(f^2))/(2*f));
G=p1+M1;
H=-2*M2;
I=p1-M1;
theta61=2*(atand((-H+(sqrt(H^2-(4*I*G))))/(2*G)));
theta62=2*(atand((-H-(sqrt(H^2-(4*I*G))))/(2*G)));
p2=(f^2-M1^2-M2^2-g^2)/(2*g);
J=p2+M1;
K=-2*M2;
L=p2-M1;
theta71=2*atand((-K+(sqrt(K^2-(4*J*L))))/(2*J));
theta72=2*atand((-K-(sqrt(K^2-(4*J*L))))/(2*J));
%Third loop
tetaid=acosd((i^2+d^2-j^2)/(2*i*d));
tetaij=acosd((i^2+j^2-d^2)/(2*i*j));
theta10=360-(tetaij-((360+theta42)-tetaid-180));
N1=(j*cosd(theta10))+(f*cosd(theta61));
N2=(j*sind(theta10))+(f*sind(theta61));
q1=((e^2)-(h^2)-(N1^2)-(N2^2))/(2*h);
J=q1+N1;
K=(-2*N2);
L=q1-N1;
theta81=2*atand((-K+(sqrt(K^2-(4*J*L))))/(2*J));
theta82=2*atand((-K-(sqrt(K^2-(4*J*L))))/(2*J));
q2=((h^2)-(e^2)-(N1^2)-(N2^2))/(2*e);
X=q2+N1;
Y=(-2*N2);
Z=q2-N1;
theta51=2*atand((-Y+(sqrt(Y^2-(4*X*Z))))/(2*X));
theta52=2*atand((-Y-(sqrt(Y^2-(4*X*Z))))/(2*X));

theta21(p,1)=theta2;
theta3(p,1)=theta31;
theta4(p,1)=theta42;
theta7(p,1)=theta51;
theta5(p,1)=theta61;
theta6(p,1)=theta72;
theta8(p,1)=theta82;
```

```
xdis=b*cosd(theta2);
ydis=b*sind(theta2);


x=0;
y=0;
for i1=1:1:16


if i1==2
x=x+a;
xdisp2(p,1)=x;
ydisp2(p,1)=y;
    hold on
if b==0.8
plot(xdisp2,ydisp2,'*r')
end
end


if i1==3
    xdisp=b*cosd(theta2);
    ydisp=b*sind(theta2);
    x=x+xdisp;
    y=y+ydisp;
    xdisp3(p,1)=x;
ydisp3(p,1)=y;



end


if i1==4
    xdisp=c*cosd(theta31);
    ydisp=c*sind(theta31);
    x=x+xdisp;
    y=y+ydisp;
     xdisp4(p,1)=x;
ydisp4(p,1)=y;


end


if i1==5
   tetaid=acosd((i^2+d^2-j^2)/(2*i*d));
    xdisp=i*cosd(360-(tetaid-theta42));
    ydisp=i*sind(360-(tetaid-theta42));
    x=x+xdisp;
    y=y+ydisp;
    xdisp5(p,1)=x;
ydisp5(p,1)=y;

end


if i1==6
    xdisp=e*cosd(180+theta51);
    ydisp=e*sind(180+theta51);
    x=x+xdisp;
    y=y+ydisp;
    xdisp6(p,1)=x;
ydisp6(p,1)=y;

end
```

```
if i1==7
    tetakh=acosd((k^2+h^2-1^2)/(2*k*h));
    xdisp=k*cosd(theta82+(180-tetakh));
    ydisp=k*sind(theta82+(180-tetakh));
    x=x+xdisp;
    y=y+ydisp;
     xdisp7(p,1)=x;
ydisp7(p,1)=y;
if theta2==0
    ht1=y;

end
if theta2==180
    ht2=y;

end
if theta2==90
    lg1=x;

end
if theta2==270
    lg2=x;

end



end


if i1==8
     x=f*cosd(theta61);
    y=f*sind(theta61);
     xdisp8(p,1)=x;
ydisp8(p,1)=y;
end


if i1==9
     x=x1(1,1);
    y=x2(1,1);
     xdisp9(p,1)=x;
ydisp9(p,1)=y;


end


if i1==10
    xdisp=x1(8,1);
    ydisp=x2(8,1);
    x=xdisp;
    y=ydisp;
end


if i1==11
    xdisp=x1(3,1);
    ydisp=x2(3,1);
    x=xdisp;
    y=ydisp;
end


if i1==12
    xdisp=x1(4,1);
    ydisp=x2(4,1);
    x=xdisp;
    y=ydisp;
end
```

```
if i1==13
    xdisp=x1(1,1);
    ydisp=x2(1,1);
    x=xdisp;
    y=ydisp;
     xdisp13(p,1)=x;
ydisp13(p,1)=y;
end

if i1==14
    xdisp=x1(5,1);
    ydisp=x2(5,1);
    x=xdisp;
    y=ydisp;
end

if i1==15
    xdisp=x1(6,1);
    ydisp=x2(6,1);
    x=xdisp;
    y=ydisp;
end

if i1==16
    xdisp=x1(8,1);
    ydisp=x2(8,1);
    x=xdisp;
    y=ydisp;
end

x1(i1,1)=x;
x2(i1,1)=y;


end


p=p+1;



end

if a==3.4||a==3.5||a==3.55||a==3.6||a==3.65||a==3.7||a==3.8



plot(xdisp7,ydisp7,'-r')
    hold on
   pause
end
ht(cr,1)=abs(ht2-ht1);
lg(cr,1)=abs(lg1-lg2);
cra(cr,1)=a;
cr=cr+1;
end
figure(2)
plot(cra,ht,'-r')
hold on
plot(cra,lg,'-r')
```

```
clear all
```

PROGRAMME FOR VARYING CRANK LINK TO PLOT STEP HEIGHT AND STEP LENGTH

```
%Link lengths

c=4.87;
i=2.58;
e=2.74;
k=6.43;
l=4.80;
g=4.88;
h=2.39;
f=2.74;
d=2.74;
j=2.40;
a=3.60;
cr=1;
for b=0.1:.01:1.25


p=1;
for theta2=0:5:360


k1=a/c;k2=a/b;k3=(d^2-c^2-a^2-b^2)/(2*b*c);
A=k3+cosd(theta2)+k2-(k1*cosd(theta2));
B=-2*sind(theta2);
C=k3-cosd(theta2)-k2-(k1*cosd(theta2));
theta31=2*atand((-B+sqrt((B^2)-(4*A*C)))/(2*A));
theta32=2*atand((-B-sqrt((b^2)-(4*A*C)))/(2*A));
k4=a/d;
k5=a/b;
k6=(c^2-a^2-b^2-d^2)/(2*b*d);
D=k6-(k4*cosd(theta2))+k5+cosd(theta2);
E=-2*sind(theta2);
F=k6-(k4*cosd(theta2))-k5-cosd(theta2);
theta41=2*atand((-E+(sqrt(E^2-(4*D*F))))/(2*D));
theta42=2*atand((-E-(sqrt(E^2-(4*D*F))))/(2*D));
%Second loop
M1=(c*cosd(theta31))+(d*cosd(theta42));
M2=(c*sind(theta31))+(d*sind(theta42));
p1=(((g^2)-(M1^2)-(M2^2)-(f^2))/(2*f));
G=p1+M1;
H=-2*M2;
I=p1-M1;
theta61=2*(atand((-H+(sqrt(H^2-(4*I*G))))/(2*G)));
theta62=2*(atand((-H-(sqrt(H^2-(4*I*G))))/(2*G)));
p2=(f^2-M1^2-M2^2-g^2)/(2*g);
J=p2+M1;
K=-2*M2;
L=p2-M1;
theta71=2*atand((-K+(sqrt(K^2-(4*J*L))))/(2*J));
theta72=2*atand((-K-(sqrt(K^2-(4*J*L))))/(2*J));
%Third loop
```

```
tetaid=acosd((i^2+d^2-j^2)/(2*i*d));
tetaij=acosd((i^2+j^2-d^2)/(2*i*j));
theta10=360-(tetaij-((360+theta42)-tetaid-180));
N1=(j*cosd(theta10))+(f*cosd(theta61));
N2=(j*sind(theta10))+(f*sind(theta61));
q1=((e^2)-(h^2)-(N1^2)-(N2^2))/(2*h);
J=q1+N1;
K=(-2*N2);
L=q1-N1;
theta81=2*atand((-K+(sqrt(K^2-(4*J*L))))/(2*J));
theta82=2*atand((-K-(sqrt(K^2-(4*J*L))))/(2*J));
q2=((h^2)-(e^2)-(N1^2)-(N2^2))/(2*e);
X=q2+N1;
Y=(-2*N2);
Z=q2-N1;
theta51=2*atand((-Y+(sqrt(Y^2-(4*X*Z))))/(2*X));
theta52=2*atand((-Y-(sqrt(Y^2-(4*X*Z))))/(2*X));

theta21(p,1)=theta2;
theta3(p,1)=theta31;
theta4(p,1)=theta42;
theta7(p,1)=theta51;
theta5(p,1)=theta61;
theta6(p,1)=theta72;
theta8(p,1)=theta82;

xdis=b*cosd(theta2);
ydis=b*sind(theta2);

x=0;
y=0;
for i1=1:1:16

if i1==2
x=x+a;
xdisp2(p,1)=x;
ydisp2(p,1)=y;
    hold on
if b==0.8
plot(xdisp2,ydisp2,'*r')
end
end

if i1==3
    xdisp=b*cosd(theta2);
    ydisp=b*sind(theta2);
    x=x+xdisp;
    y=y+ydisp;
    xdisp3(p,1)=x;
ydisp3(p,1)=y;


end

if i1==4
    xdisp=c*cosd(theta31);
    ydisp=c*sind(theta31);
    x=x+xdisp;
    y=y+ydisp;
    xdisp4(p,1)=x;
```

```
ydisp4(p,1)=y;

end

if i1==5
  tetaid=acosd((i^2+d^2-j^2)/(2*i*d));
   xdisp=i*cosd(360-(tetaid-theta42));
   ydisp=i*sind(360-(tetaid-theta42));
   x=x+xdisp;
   y=y+ydisp;
   xdisp5(p,1)=x;
ydisp5(p,1)=y;
end

if i1==6
   xdisp=e*cosd(180+theta51);
   ydisp=e*sind(180+theta51);
   x=x+xdisp;
   y=y+ydisp;
   xdisp6(p,1)=x;
ydisp6(p,1)=y;
end

if i1==7
   tetakh=acosd((k^2+h^2-l^2)/(2*k*h));
   xdisp=k*cosd(theta82+(180-tetakh));
   ydisp=k*sind(theta82+(180-tetakh));
   x=x+xdisp;
   y=y+ydisp;
    xdisp7(p,1)=x;
ydisp7(p,1)=y;
if theta2==0
   ht1=y;
end
if theta2==180
   ht2=y;
end
if theta2==90
   lg1=x;
end
if theta2==280
   lg2=x;
end



end

if i1==8
    x=f*cosd(theta61);
   y=f*sind(theta61);
    xdisp8(p,1)=x;
ydisp8(p,1)=y;
end

if i1==9
    x=x1(1,1);
   y=x2(1,1);
    xdisp9(p,1)=x;
ydisp9(p,1)=y;
```

```
end

if i1==10
    xdisp=x1(8,1);
    ydisp=x2(8,1);
    x=xdisp;
    y=ydisp;
end

if i1==11
    xdisp=x1(3,1);
    ydisp=x2(3,1);
    x=xdisp;
    y=ydisp;
end

if i1==12
    xdisp=x1(4,1);
    ydisp=x2(4,1);
    x=xdisp;
    y=ydisp;
end

if i1==13
    xdisp=x1(1,1);
    ydisp=x2(1,1);
    x=xdisp;
    y=ydisp;
     xdisp13(p,1)=x;
ydisp13(p,1)=y;

if i1==14
    xdisp=x1(5,1);
    ydisp=x2(5,1);
    x=xdisp;
    y=ydisp;
end

if i1==15
    xdisp=x1(6,1);
    ydisp=x2(6,1);
    x=xdisp;
    y=ydisp;
end

if i1==16
    xdisp=x1(8,1);
    ydisp=x2(8,1);
    x=xdisp;
    y=ydisp;
end

x1(i1,1)=x;
x2(i1,1)=y;


end
```

```
p=p+1;


end
b
if b==0.8||b==0.9||b==1.0||b==1.12||b==1.21||b==1.25

        b
        lg1
        lg2
        abs(lg1-lg2)
        ht1
        ht2
        abs(ht2-ht1)
plot(xdisp7,ydisp7,'-r')
    hold on
    pause
end
ht(cr,1)=abs(ht2-ht1);
lg(cr,1)=abs(lg1-lg2);
cra(cr,1)=b;

cr=cr+1;
end
figure(2)
plot(cra,ht,'-r')
hold on
plot(cra,lg,'-r')

clear all
```