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Influence of joint clearance on kinematic and dynamic parameters of mechanism

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Abstract: *Kinematic joints for dynamic analysis of multi-body mechanical systems assumed ideal or perfect. However, in a real mechanical kinematical joint clearance is always present. Such clearance is necessary for the component assemblage and to allow the relative motion between the connected bodies. This clearance is inevitable due to the manufacturing tolerances, material deformations, wear, and imperfections. The presence of such joint clearance degrades the performance of mechanical systems in virtue of the contact and impact forces that take place at the joint. Contact analysis is a computational bottleneck in mechanical design where the contact changes. Manual analysis is time-consuming and prone to error. To address these problems, a geometrical contact analysis method based on kinematic simulation, using CAD software is developed. An equivalent kinematic linkage mechanism is constructed according to contact position of pin and hole assembly. Results of kinematic and dynamic analysis of a four bar linkage with joint clearance shows that the contribution of joint forces at slower input speed also degrades the performance of mechanism.*
Keywords: *Clearance link, equivalent mechanism, joint forces, degree of freedom.*

Nomenclature

Length of link (mm), L_i
Angular position of links (°), θi
Clearance link at joint (mm), C_{li}
Angular position of clearance links (°), ψ_i
Length of equivalent link (mm), L_{ei}
Angular position of equivalent links (°),$\boldsymbol{\varphi}_i$
Angular velocity (rad/sec), ω
Angular Acceleration (rad/sec^2), $\acute{\omega}$
Joint Force (N), F
Clearance (mm), c
Number of links, N
Density (kg/m^3), ρ
Poisson's Ratio, υ
Young's Modulus (kg/m^2), E

I. Introduction

Ideal revolute joint has only one axial rotational degree of freedom. It is a common and unconstrained axis of the revolute joint. In a 3-D revolute clearance joint, one degree of freedom added between pin and hole assembly. Such assembly is under presence of different external forces such as contact, impact, friction, gravity etc. In this study pure contact method is addressed. The position of contact point during the rotation of linkages is unpredictable. Exact position is extracted from the 2-D constraint simulation of the four bar mechanism with clearance joint. Exact contact position gives the instantaneous maximum clearance between pin and hole. It is a geometrical approach to extract the contact point. A mass-less clearance link is constructed, which gives the instantaneous equivalent mechanism. Analysis of set of such instantaneous equivalent mechanism gives the variation in kinematic and dynamic parameters.

The performance deviation due to clearance in joint was addressed in previous work with different methodology. A geometrical model was used to explain and assess the output position or direction variation, to predict the limit of position uncertainty and to determine the maximum clearance. [1] A four-bar mechanism having two joints with clearance was considered as a model mechanism. A neural network was used to model several characteristics of joint clearance. Kinematic and dynamic analyses were achieved using continuous contact mode between journal and bearing. Kinematic analysis of the model mechanism comprises determining of displacements, velocities and accelerations of the mass centers of moving links. Loop closure equation from the vector representation of the clearance link was used for the analysis. [2] Equations are derived that describes

the condition of clearance revolute joint without considering the hydrodynamic lubrication. The equations are governed by dimensionless parameter that depends on nominal motion, mass distribution and influence coefficient of the linkage in which the joint appears with clearance. [3]
There are four sub cases of contact configurations. These are no contact, one point contact, two points contact, and line contact. There are four main modeling strategies for mechanical systems with revolute clearance joints, namely, the mass-less link approach, the spring–damper approach, the momentum exchange approach and FEM approach. Equations of motion of plane multilink mechanism with clearances were constructed by Hiroaki in 1978. Two joints with clearances and pure contact of a four bar mechanism were considered. [4] Typical contact-impact force models with dissipated effects are dependent on the contact velocities, and therefore, it is important to evaluate these velocities in order to account for the dissipative effects during the contact-impact process. [6] It has been observed that, in single loop linkage, joint clearances with same value contribute equally to deviation of the link from its ideal position. It is possible to assess the output position or direction variation, due to clearances allocated at the joints, by using geometrical model. [8]

In this study, 2-D kinematic four bar mechanism is considered. Three joints with clearance are simulated for the additional degree of freedom occurred due to clearances in CAD software. Max clearance of 0.5 mm at the joint is assumed for the analysis. Twelve crank positions are considered for the study. The clearance link is constructed according to the contact position between pin and hole bearing surface of link. Equivalent linkage is constructed for twelve position and angular position for clearance link (ψ) and equivalent link (φ) is determined. Ideal four bar mechanism and set of twelve equivalent mechanisms are kinematically and dynamically analyzed in multi-body dynamic analysis software. The variation in angular velocity and angular acceleration of all four joints of ideal four bar mechanism and equivalent mechanisms were recorded. Similarly, joint forces were also recorded and compared with ideal mechanism.

Linkage parameters of proven example [13] are considered for the validation of approach used for the kinematic analysis of the four bar mechanism.

II. Contact Position Analysis

2.1 Joint Clearance The joint clearance is the difference of the diameters of the pin and hole of a joint. Fig-1 shows the enlarged view clearance link (*c*), which is a mass-less link. Minimum 20 to 30 microns clearance is required for assembly and to have relative motion between parts. In a revolute joint, joint clearance *c* is defined as the difference between the radii of bearing and journal, r_B and r_J, respectively. If there is no lubrication, the journal can move freely within the bearing until any contact between the two bodies take place. If the friction is negligible, the direction of joint clearance vector coincides with the direction of normal force at the contact point. When the continuous contact mode assumption between journal and bearing at each joint is considered, the clearances may be modeled as vectors which correspond to mass-less virtual links with the lengths equal to joint clearance. The clearance can be defined as,
$c = r_B - r_J$ ……………………[2.1]
Each joint clearance adds additional freedom to the mechanism, and additional constraints are necessary to analyze the system. [10]

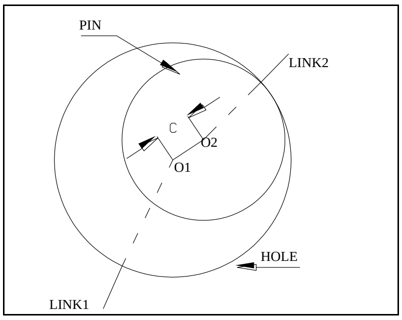

Fig-1: A clearance link

A line diagram of ideal mechanism with linkage parameters is given in fig-2. Crank, coupler and the follower are connected together and all four revolute joints are assumed perfect, i.e. without clearance.

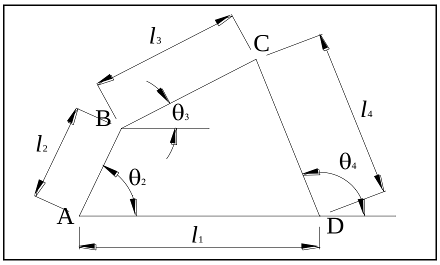

Fig-2: Linkage Parameter of Ideal four bar mechanism

Assuming constant contact between the pin and hole of a joint, a joint clearance may be modeled as a small link (called clearance link) with the length equal to one half of the joint clearance. Thus, a single degree of freedom four bar linkage would become a five degree of freedom eight bar linkage as shown in fig-3. Each joint clearance adds one degree of freedom to the linkage. The direction uncertainty due to the joint clearance is thus represented by the added redundant degree of freedom in the linkage.

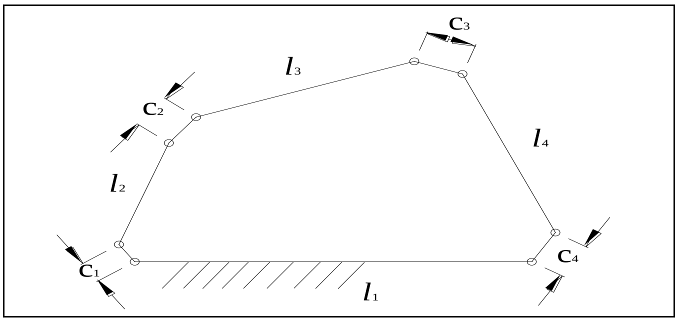

Fig-3: A eight bar linkage with joint clearance

2.2 Rotatability Laws of Linkages An '*n'* degree-of-freedom linkage is defined as a fully rotatable linkage, if the linkage will never encounter a dead position, where the linkage would temporarily lose its mobility. A linkage is fully rotatable if,

1) The linkage has a class I chain
2) Each short link has an input joint on it and
3) Each input joint connects at least one short link

In a class I chain, the three longest links are called long links and the remaining links are short links. The sum of the lengths of all short links can never be greater than the length of any long link. A class I chain has the following rotatability properties.

a. Each short link can be made to have a complete rotation with respect to any link in the chain.
b. Any pair of long links can never become collinear or parallel to each other.
c. The rotation range between two long links is always less than 180°[1].

Let l_1, l_3 and l_4 be the three long links and l_2 is the short link. The angle θ between any pair of long links, say l_2 and l_3, must be in the range of $\theta_{min} \leq \theta \leq \theta_{max}$, where,

$$\theta_{min} = \cos^{-1}\{[\, l_1^2 + l_3^2 - (l_4 - l_2)^2]/(2\, l_1 + l_3)\} \quad \text{…[2.2]}$$

$$\theta_{max} = \cos^{-1}\{[\, l_1^2 + l_3^2 - (l_4 + l_2)^2]/(2\, l_1 + l_3)\} \quad \text{…[2.3]}$$

2.3 Rotatability of Linkages with Clearance Links Each joint clearance represented by a clearance link, an N-bar linkage is equivalent to a (2N)-bar linkage and the number of degree of freedom is increased from (N - 3) to (2N - 3). Because the sum of all clearance link lengths is much smaller than any nominal link length, adding clearance links does not change the classification of the resulting chain, unless the nominal linkage has a class III chain or one close to a class III chain.

If each of the (N - 3) inputs is given between two nominal links, the equivalent linkage still has N degrees of freedom. The additional freedom is due to the uncertainty caused by the joint clearance. By giving random inputs to the N clearance links, the uncertain rotation region between nominal links can be determined. [1]

2.4 Contact Prediction Contact points at different positions of the mechanism are determined from contact position. Similar approach is followed for all three clearance revolute joint.

A four bar mechanism is constructed in CAD software considering the constraints due to clearance and simulated for the one revolution. A joint clearance mechanism is constructed with clearance of 0.5 mm. The mechanism is constructed with additional degree of freedom. This mechanism is kinematically simulated for additional degree of freedom. The construction is given in fig-4 and fig-5 for 30° crank position. Contact point is marked from the kinematic position and linkage parameters of the clearance link are measured from the CAD geometry. Thus the resultant link called as equivalent link is investigated. The equivalent linkage for each position is generated and analyzed with multi-body dynamic analysis software. Similar steps are followed for the twelve crank positions in one rotation. Position of the point of contact and clearance link for one revolution in the step of 30° are investigated and tabulated in table-1.

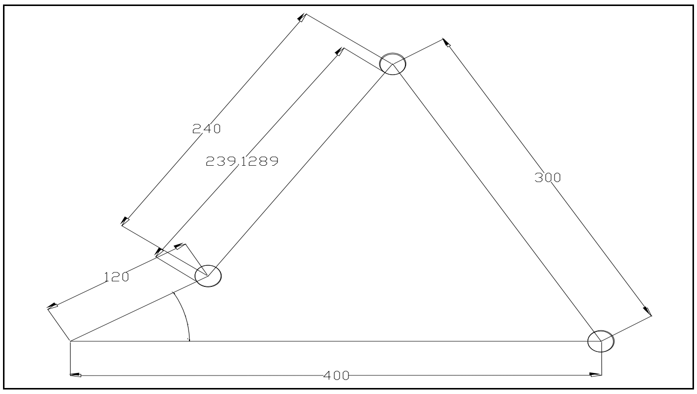

Fig-4: Contact Position of a revolute joint with clearance

Table-1 Position of Clearance link in one revolution

Pos No	Cl_2, mm	Cl_3, mm	Cl_4, mm	ψ_2, °	ψ_3, °	ψ_4, °
1	0.5	0.5	0.5	68.680	129.076	129.076
2				53.575	119.480	119.480
3				39.200	119.179	119.179
4				28.590	126.986	126.986
5				21.522	139.297	139.297
6				18.172	152.620	152.620
7				20.896	162.709	162.709
8				31.752	166.200	166.200
9				46.984	164.759	164.759
10				61.989	160.384	160.384
11				73.192	153.171	153.171
12				76.487	142.391	142.391
13				68.680	129.076	129.076

III. Equivalent Linkage

When the continuous contact mode between journal and bearing at a joint has occurred, the clearance vector is equal to the difference between journal and bearing radii. In the presence of clearance at a revolute joint, the two kinematic constraints lost, and two degrees of freedom consisting of the horizontal and vertical displacements of the journal center relative to bearing center are added to the mechanism motion. These movements may lead to uncertainties in the motion of mechanism. So, additional constraints are necessary to analyze the kinematics of a system.

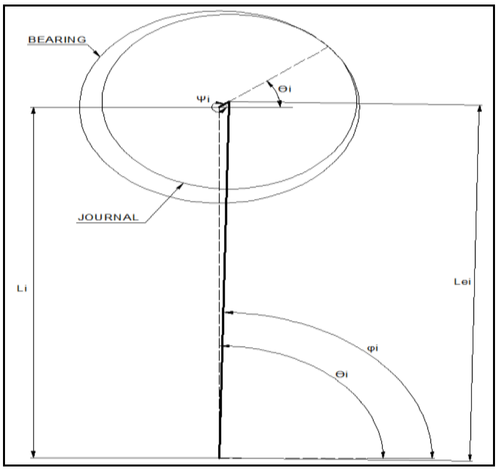

Fig-5: Linkage Parameter of 4-R mechanism with clearance at joints.

Linkage parameters of ideal mechanism are tabulated below in table-2.

Table-2 Linkage Parameters of ideal four bar mechanism in one revolution

Pos No	l_1, mm	l_2, mm	l_3, mm	l_4, mm	θ_1, °	θ_2, °	θ_3, °	θ_4, °
1	120	250	300	400	0	248.680	129.076	180
2					30	233.575	119.480	
3					60	219.200	119.179	
4					90	208.590	126.986	
5					120	201.522	139.297	
6					150	198.172	152.620	
7					180	200.896	162.709	
8					210	211.752	166.200	
9					240	226.984	164.759	
10					270	241.989	160.384	
11					300	253.192	153.171	
12					330	256.487	142.391	
13					360	248.680	129.076	

Equivalent linkage is the resultant vector of the nominal link and the clearance link. Equivalent link is constructed considering the clearance of 0.5 mm which is exaggerated clearance used for the study. Linkage parameters (i.e. equivalent link and its position) are determined and the details are given in table-3.

Table-3 Linkage Parameters of four bar mechanism with joint clearances in one revolution

Pos No	le_1, mm	le_2, mm	le_3, mm	le_4, mm	φ_1, °	φ_2, °	φ_3, °	φ_4, °
1	120.183	249.747	299.685	400	0.222	68.774	129.076	180
2	120.458	249.705	299.754	400	30.095	53.618	119.48	180
3	120.917	248.687	299.756	400	59.256	39.514	119.179	180
4	120.24	249.427	299.699	400	89.791	28.547	126.986	180
5	119.927	249.267	299.621	400	119.764	21.577	139.297	180
6	119.667	249.15	299.556	400	149.822	18.221	152.62	180
7	119.553	249.107	299.523	400	179.915	20.946	162.709	180
8	119.5	249.15	299.514	400	209.976	31.817	166.2	180
9	119.513	249.5	299.518	400	240.035	46.965	164.759	180
10	119.559	249.427	299.529	400	270.113	62.078	160.384	180
11	119.658	249.587	299.554	400	300.175	73.273	153.171	180
12	119.859	249.705	299.604	400	330.229	76.548	142.391	180
13	120.183	249.787	299.685	400	359.988	68.724	129.076	180

The variation in the nominal lengths of crank, coupler and follower of an equivalent linkage are graphically shown in fig-6 to fig-8. Variation in nominal crank is from 0.76% minimum to 0.42 % maximum. Variation in the nominal coupler is from 0.52% maximum to 0.08% minimum, similarly for the follower 0.16% maximum to 0.18% minimum. This variations obtained on the linkage parameters is much higher than tolerances provided on the linkage.

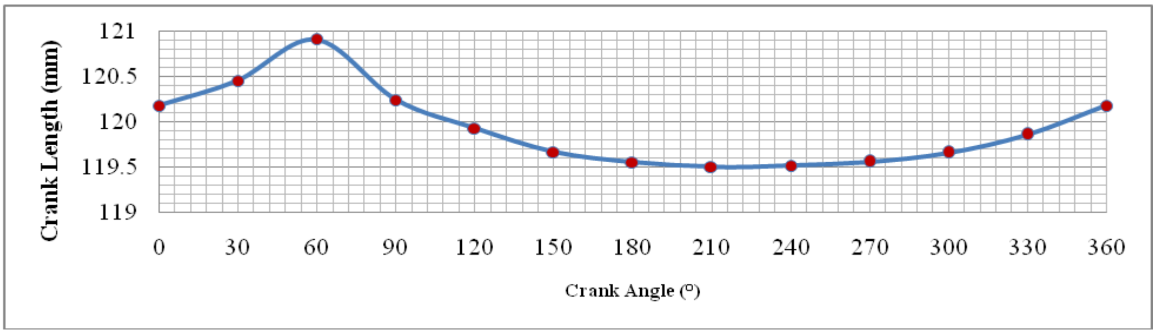

Fig-6: Variations in equivalent crank

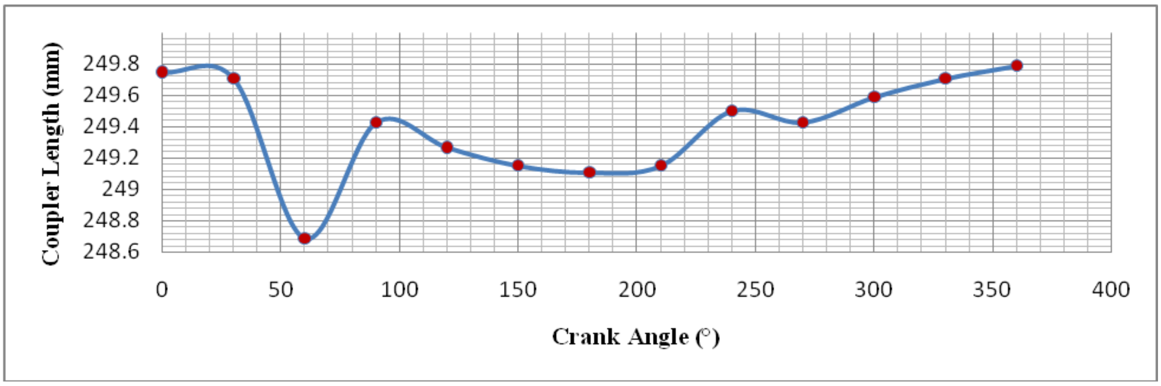

Fig-7: Variations in equivalent coupler

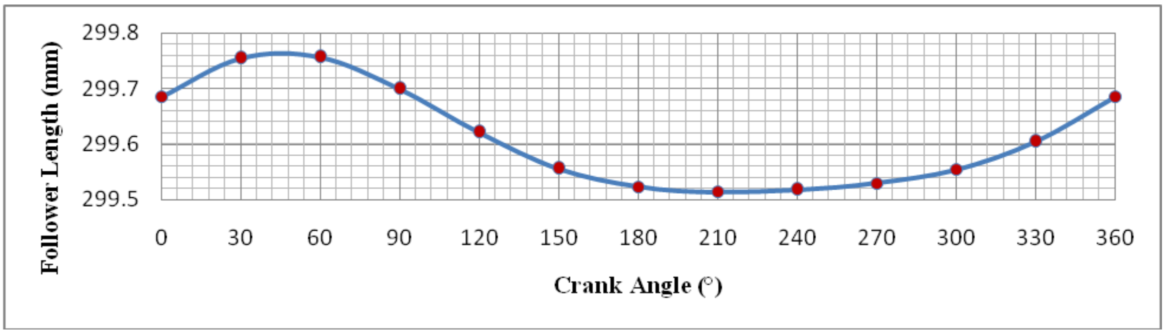

Fig-8: Variations in equivalent follower

IV. Analysis Of Four Bar Mechanism

Ideal four bar mechanism is constructed in multi-body dynamic software. Results for kinematic and dynamic analysis are extracted. Similarly, set of twelve equivalent four bar mechanisms are constructed and variations in the angular velocity, angular acceleration of links and the joint forces are recorded.

4.1 Linkage Parameters Steel is assumed as linkage material for the analysis. Material Properties are given below. Linkage mass and inertia is tabulated in table-4.
Density (ρ) 7801 kg/m^3
Poisson's Ratio (υ) 0.29
Young's Modulus (E) 2.07E+05 N/mm^2

Table-4 Linkage mass & Inertia

Link	Mass (kg)	Mass Moment of Inertia (kgmm^2)		
		I_{XX}	I_{YY}	I_{ZZ}
Fixed Link	0.408883	6015.3905	5995.2036	21.890611
Crank	0.135848	227.64994	221.11475	7.1012155
Coupler	0.262614	1602.8785	1590.005	13.967721
Follower	0.311371	2664.1874	2648.8761	16.608684

Dynamic parameters of the four bar mechanism are investigated for lower and higher crank Speed of 5 rpm and 1500 rpm respectively.

4.2 Kinematic Analysis Kinematic analysis is carried out. Results of angular velocities and angular accelerations of four revolute joints are determined and the plot of angular velocity vs crank angle of ideal four bar mechanism is shown in fig-9 and fig-10. Similarly, plots of angular acceleration vs crank angle of ideal four bar mechanism shown in fig-11 and fig-12.

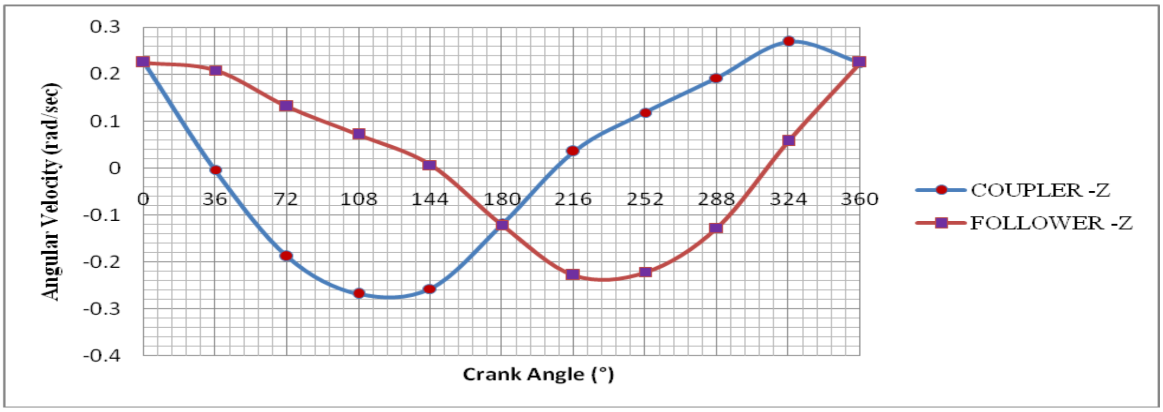

Fig-9: Plot of angular velocity of coupler and follower (5 rpm crank speed)

The angular velocity and angular acceleration of equivalent mechanism are recorded and tabulated in table-5 and table-6. Joint between crank and coupler is denoted by Joint-2, whereas between coupler and follower and follower with the fixed link is denoted by Joint-3 and Joint-4 respectively.

Table-5 Angular Velocity of ideal four bar mechanism (5 rpm Crank Speed)

5 rpm Ideal	Angular Velocity (rad/sec)					
Position, °	Coupler	Follower	Joint-1	Joint-2	Joint-3	Joint-4
0	0.2245	0.2245	0.5238	0.7483	0	0.2245
36	-0.0041	0.2081	0.5238	0.5197	0.2123	0.2081
72	-0.1885	0.1307	0.5238	0.3353	0.3192	0.1307
108	-0.2677	0.0716	0.5238	0.2561	0.3393	0.0716
144	-0.2565	0.0064	0.5238	0.2673	0.2629	0.0064
180	-0.1205	-0.1212	0.5238	0.4033	0	0.1212
216	0.0356	-0.2279	0.5238	0.5594	0.2635	0.2279
252	0.1177	-0.2216	0.5238	0.6416	0.3394	0.2216
288	0.1918	-0.1272	0.5238	0.7156	0.319	0.1272
324	0.2688	0.0572	0.5238	0.7926	0.2116	0.0572
360	0.2238	0.2248	0.5238	0.7476	0	0.2248
Max	0.2773	0.2378	0.524	0.801	0.341	0.238
Min	-0.275	-0.2369	0.524	0.249	0	0.006

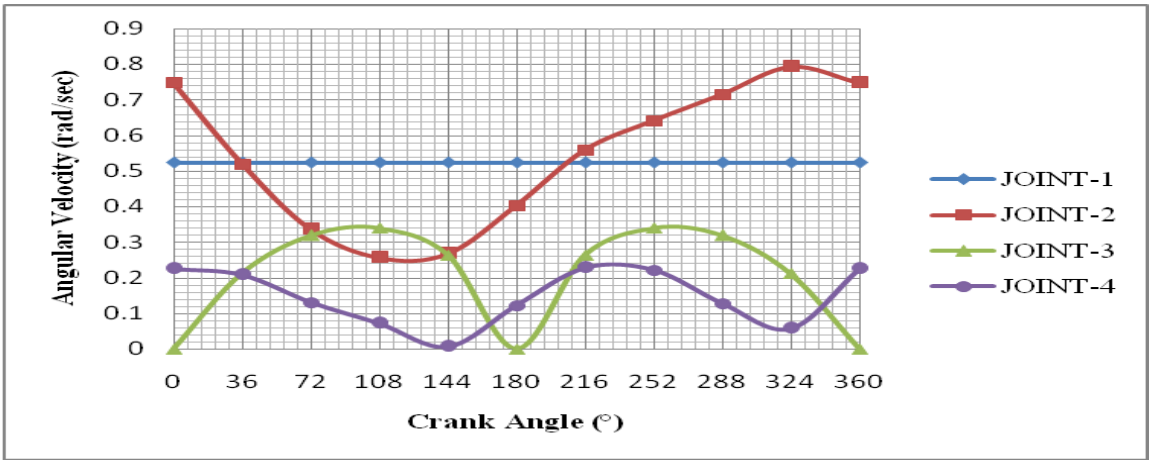

Fig-10: Plot of angular velocity of revolute joint (5rpm crank speed)

Max angular velocity of coupler is 0.2773 rad/sec and that of follower is 0.2378 rad/sec. Whereas minimum angular velocity of coupler is 0.2750 rad/sec and of follower is 0.2369 rad/sec.

Table-6 Angular Acceleration of ideal four bar mechanism (5 rpm Crank Speed)

5 RPM Ideal	**Angular Acceleration (rad/sec^2)**					
Position, °	**Coupler -Z**	**Follower -Z**	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
0	-0.1365	0.0655	0	0.1365	0.2019	0.0655
36	-0.1979	-0.063	0	0.1979	0.1349	0.063
72	-0.1061	-0.0572	0	0.1061	0.0489	0.0572
108	-0.0294	-0.0452	0	0.0294	0.0158	0.0452
144	0.0553	-0.0733	0	0.0553	0.1287	0.0733
180	0.1563	-0.1273	0	0.1563	0.2835	0.1273
216	0.0905	-0.0375	0	0.0905	0.128	0.0375
252	0.0581	0.0426	0	0.0581	0.0155	0.0426
288	0.068	0.1172	0	0.068	0.0492	0.1172
324	0.0426	0.178	0	0.0426	0.1353	0.178
360	-0.1372	0.0647	0	0.1372	0.2019	0.0647
Max	0.1563	0.178	0	0.2071	0.2835	0.178
Min	-0.2071	-0.1273	0	0.0005	0.0018	0.0013

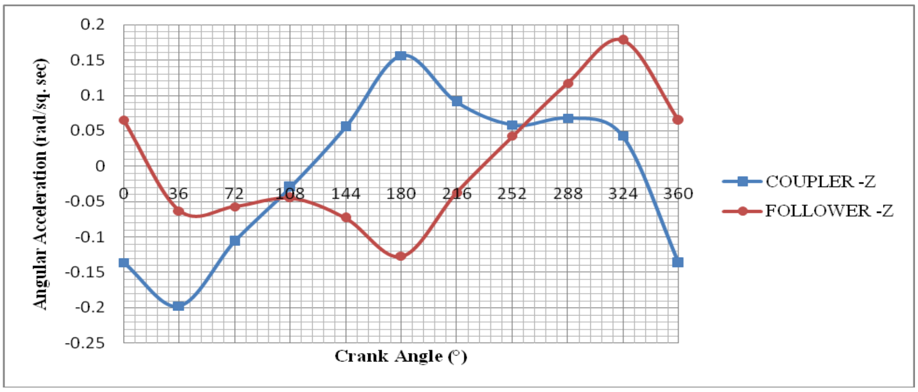

Fig-11: Plot of angular acceleration of coupler and follower (5rpm crank speed)

Max angular acceleration of coupler is 0.1563 rad/sec^2 and of follower is 0.1780 rad/sec^2, whereas minimum angular acceleration of coupler is 0.2071 rad/sec^2 and of follower is 0.1273 rad/sec^2

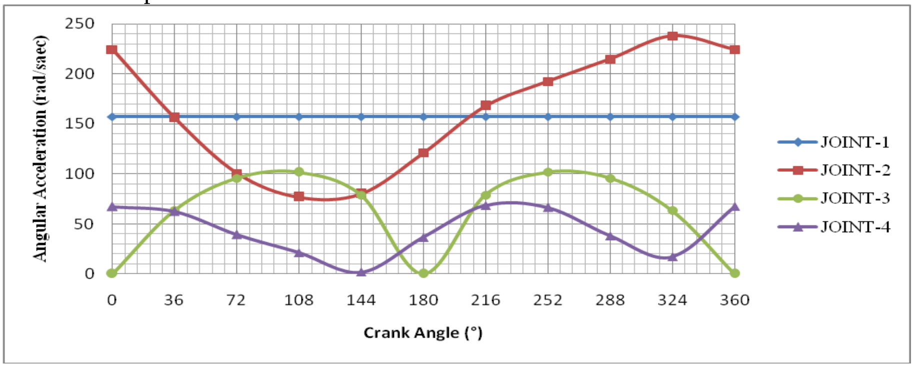

Fig-12: Plot of angular acceleration of revolute joints (5 rpm crank speed)

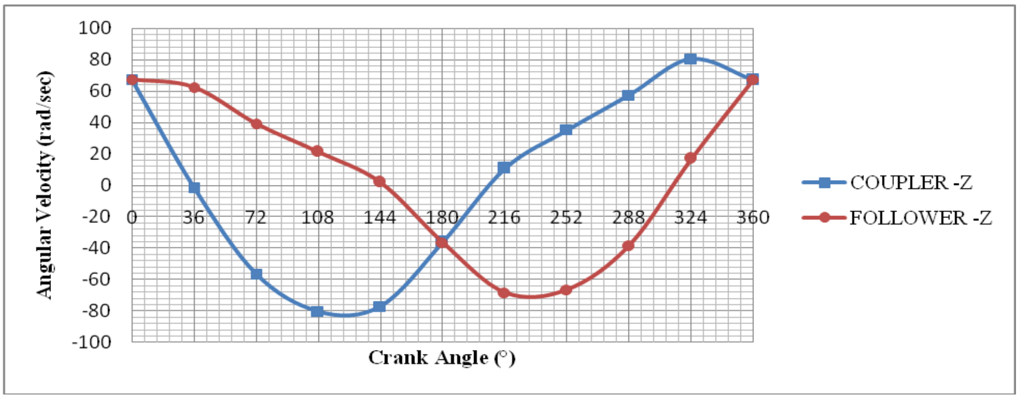

Fig-13: Plot of angular velocity of coupler and follower (1500 rpm crank speed)

Table-7 Angular velocity of ideal four bar mechanism (1500 rpm crank speed)

1500 RPM Ideal	Angular Velocity (rad/sec)					
Position, °	**Coupler -z**	**Follower -z**	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
0	67.3469	67.3469	157.143	224.4898	0	67.3469
36	-1.2402	62.4438	157.143	155.9027	63.684	62.4438
72	-56.5507	39.2099	157.143	100.5922	95.7606	39.2099
108	-80.299	21.4947	157.143	76.8438	101.794	21.4947
144	-76.9453	1.9293	157.143	80.1975	78.8747	1.9293
180	-36.1506	-36.3559	157.143	120.9923	0.2053	36.3559
216	10.6832	-68.3773	157.143	167.826	79.0605	68.3773
252	35.323	-66.4934	157.143	192.4659	101.816	66.4934
288	57.5385	-38.151	157.143	214.6814	95.6895	38.151
324	80.6485	17.1602	157.143	237.7913	63.4883	17.1602
360	67.1487	67.4412	157.143	224.2916	0.2925	67.4412
Max	80.6485	67.4412	157.143	237.7913	101.816	68.3773
Min	-80.299	-68.3773	157.143	76.8438	0.2053	1.9293

Maximum and minimum angular velocity plot of coupler and follower at constant crank speed of 1500 rpm is shown in fig-13 and plot of angular velocity of revolute joint is shown in fig-14. Maximum angular velocity of coupler is 80.6485 rad/sec and of follower is 67.4412 rad/sec and minimum angular velocity of coupler is 80.299 rad/sec of follower is 68.3773 rad/sec. Angular velocity and angular acceleration of coupler; follower and all four revolute joints are tabulated in table-7 and table-8. Plot of angular acceleration is shown in fig-15.

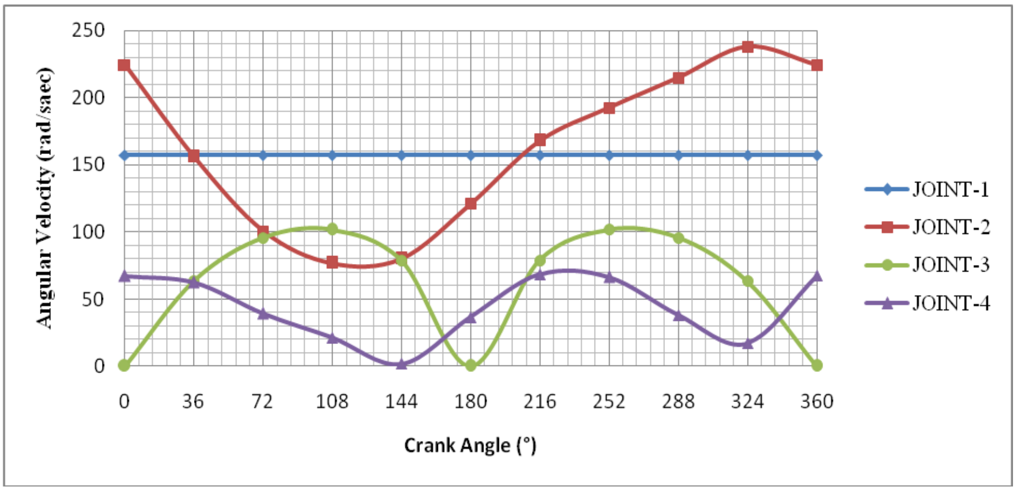

Fig-14: Plot of angular velocity of revolute joint (1500 rpm crank speed)

Table-8 Angular acceleration of ideal four bar mechanism (1500 rpm crank speed)

1500 RPM Ideal	Angular Acceleration (rad/sec^2)					
Position, °	**Coupler -z**	**Follower -z**	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
0	-12281.26	5892.2116	0	12281.26	18173.472	5892.2116
36	-17809.6841	-5668.0411	0	17809.684	12141.643	5668.0411
72	-9549.8262	-5145.0176	0	9549.8262	4404.8086	5145.0176
108	-2649.9623	-4068.4178	0	2649.9623	1418.4556	4068.4178
144	4980.1187	-6598.6945	0	4980.1187	11578.813	6598.6945
180	14062.8959	-11455.7728	0	14062.896	25518.669	11455.773
216	8141.476	-3374.8853	0	8141.476	11516.361	3374.8853
252	5224.8044	3832.3484	0	5224.8044	1392.456	3832.3484
288	6117.8017	10547.6119	0	6117.8017	4429.8102	10547.612
324	3837.8292	16015.5853	0	3837.8292	12177.756	16015.585
360	-12352.1408	5821.1997	0	12352.141	18173.341	5821.1997
Max	14062.8959	16015.5853	0	17809.684	25518.669	16015.585
Min	-17809.6841	-11455.7728	0	2649.9623	1392.456	3374.8853

Fig-15: Plot of angular acceleration of revolute joints (1500 rpm crank speed)

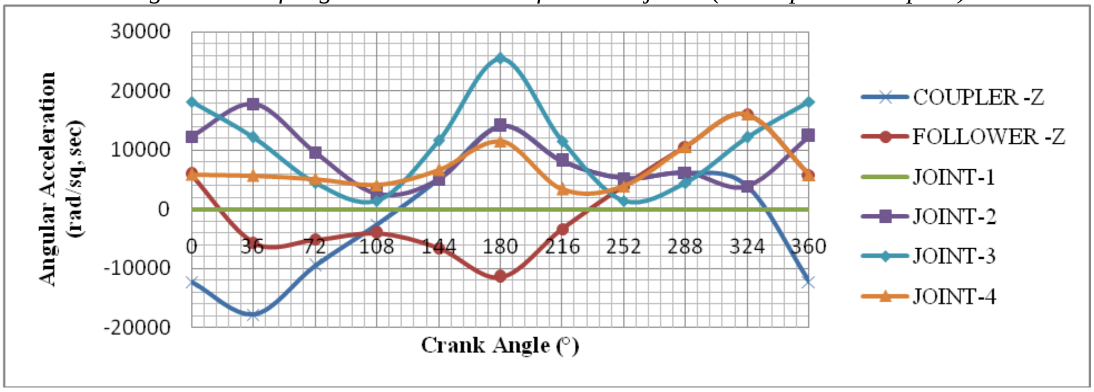

Table-9 Variation of angular velocity of four bar mechanism (5 rpm crank speed)

Position, °	Max angular velocity (rad/sec) at 5 RPM					
	Coupler	**Follower**	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
Ideal	83.195	71.333	157.14	240.34	102.43	71.333
Four bar mechanism with clearance joint						
0	83.53	71.4948	157.14	240.67	102.48	71.495
30	83.849	71.7689	157.14	240.99	102.91	71.769
60	84.498	72.0782	157.14	241.64	103.89	72.078
90	83.698	71.6111	157.14	240.84	103.07	71.611
120	83.46	71.1929	157.14	240.84	103.07	71.611
150	83.136	70.9717	157.14	240.28	102.44	70.972
180	83.074	71.0298	157.14	240.22	102.35	71.03
210	83.146	71.0645	157.14	240.29	102.31	71.065
240	83.08	71.1371	157.14	240.22	102.37	71.137
270	83.16	71.0349	157.14	240.3	102.2	71.035
300	83.119	70.9498	157.14	240.26	102.2	70.95
330	83.109	71.1705	157.14	240.25	102.27	71.171
360	83.466	71.5365	157.14	240.61	102.65	71.537
Max	84.498	72.0782	157.14	241.64	103.89	72.078
Min	83.074	70.9498	157.14	240.22	102.2	70.95

Twelve crank positions of four bar mechanism with three clearance revolute joints are analyzed. The variations in angular velocity of coupler and follower are observed 1.59% and 1.05% respectively for slower crank speed of 5 rpm. Angular velocity of coupler and follower, for higher crank speed of 1500 rpm has variations of 1.57% and 1.04%. The variations in maximum angular velocity of coupler, follower and joints at constant crank speed of 5 rpm are shown in fig-16 to fig-18, which is tabulated at table-9.

Similarly, variations of angular velocity of coupler, follower and revolute joints of four bar mechanism at constant crank speed of 1500 rpm is shown in fig-19 to fig-21, respective data is placed at table-10.

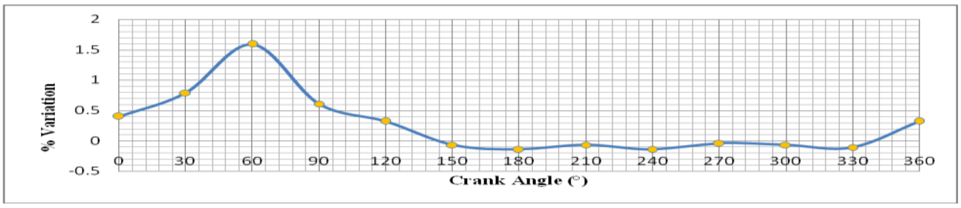

Fig-16: Plot of variation in maximum angular velocity of coupler (5 rpm crank speed)

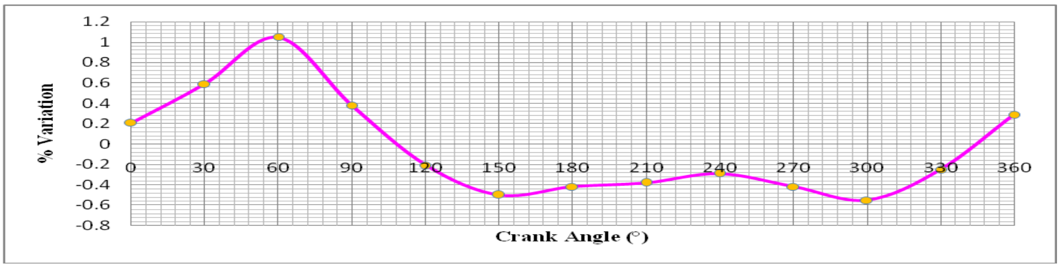

Fig-17: Plot of variation in maximum angular velocity of follower (5 rpm crank speed)

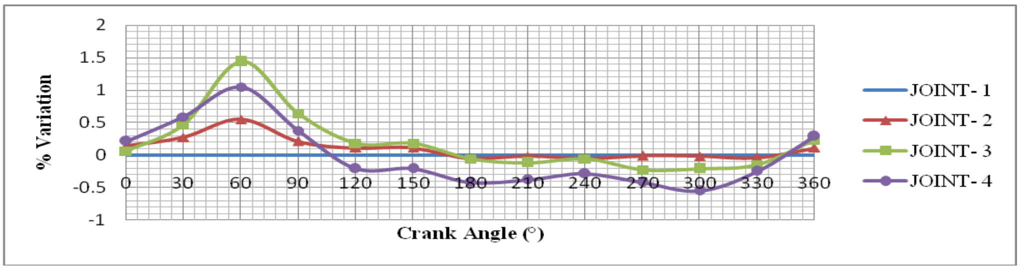

Fig-18: Plot of percentage variation in maximum joint velocity (crank speed 5 rpm)

Table-10 Variation of angular velocity of four bar mechanism (1500 rpm crank speed)

Position	Max Angular Velocity (rad/sec)					
	Coupler	Follower	Joint 1	Joint 2	Joint 3	Joint 4
1500 rpm Ideal	83.1951	71.333	157.143	240.338	102.432	71.333
Four Bar Mechanism With Clearance at Revolute Joint						
0	83.5298	71.4948	157.143	240.673	102.477	71.495
30	83.8487	71.7689	157.143	240.992	102.912	71.769
60	84.4983	72.0782	157.143	241.641	103.891	72.078
90	83.6979	71.6111	157.143	240.841	103.067	71.611
120	83.4598	71.1929	157.143	240.841	103.067	71.611
150	83.1359	70.9717	157.143	240.279	102.441	70.972
180	83.0741	71.0298	157.143	240.217	102.348	71.03
210	83.1457	71.0645	157.143	240.289	102.313	71.065
240	83.0803	71.1371	157.143	240.223	102.373	71.137
270	83.1604	71.0349	157.143	240.303	102.196	71.035
300	83.1193	70.9498	157.143	240.262	102.203	70.95
330	83.1088	71.1705	157.143	240.252	102.272	71.171
360	83.4657	71.5365	157.143	240.609	102.65	71.537
MAX	84.4983	72.0782	157.143	241.641	103.891	72.078
MIN	83.0741	70.9498	157.143	240.217	102.196	70.95

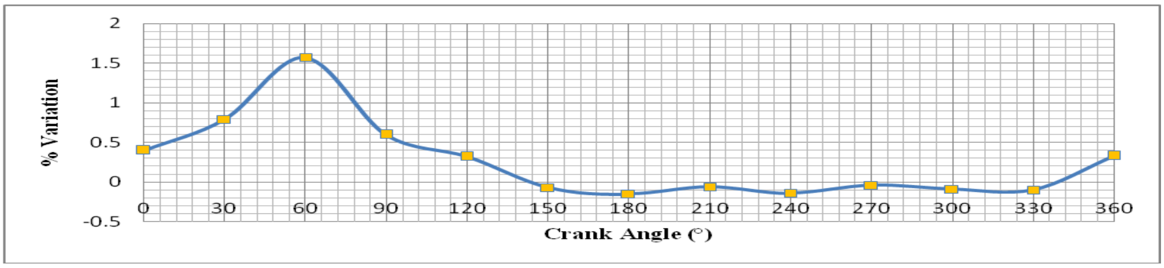

Fig-19: Plot of variation in maximum angular velocity of coupler (1500 rpm crank speed)

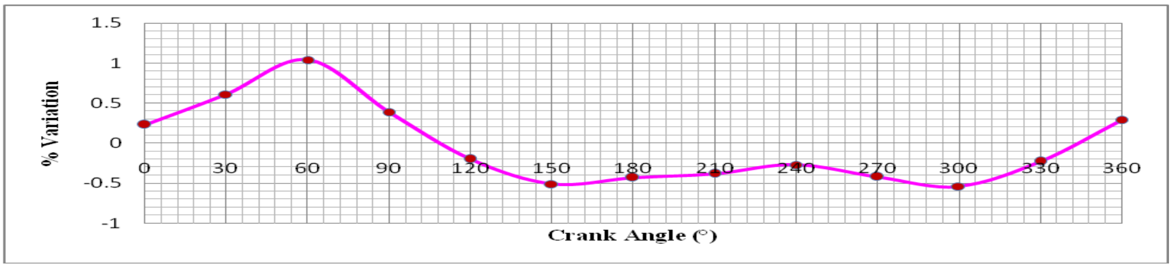

Fig-20: Plot of variation in maximum angular velocity of follower (1500 rpm crank speed)

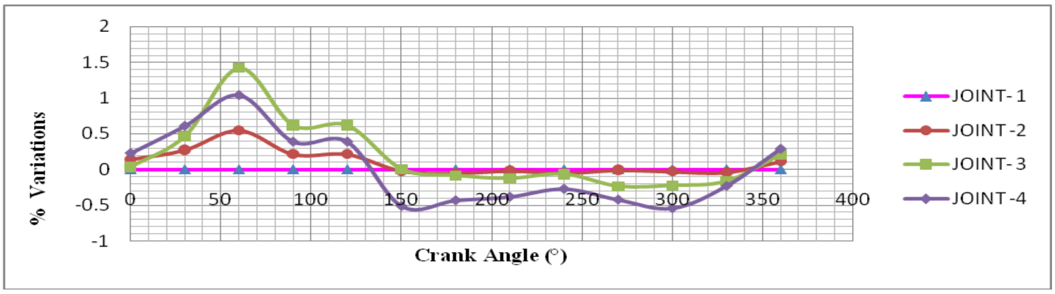

Fig-21: Plot of percentage variation in maximum joint velocity (crank speed 1500 rpm)

4.3 Dynamic Analysis A mechanism is constructed in ADAMS multi body dynamic analysis software for twelve crank positions of the equivalent linkage parameters, which are investigated from CAD simulation of clearance joints. Joint forces are determined for the 90° crank position, form the dynamic analysis of a ideal four bar mechanism with joint clearance.

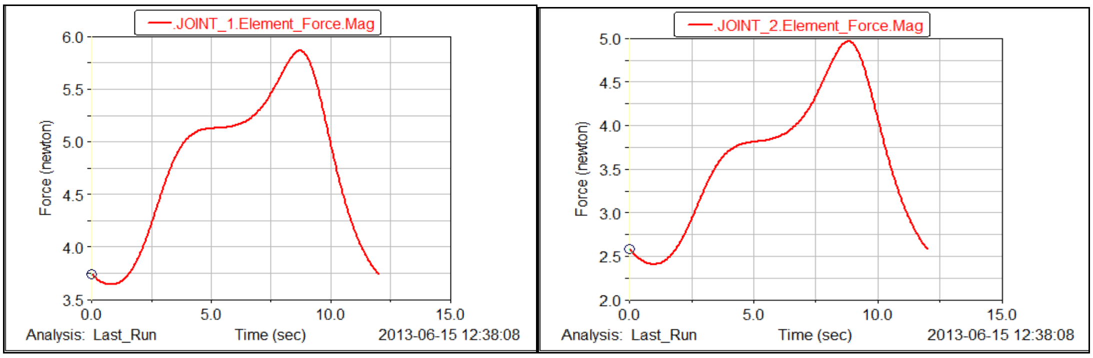

Fig-22: Element force at joint 1 and joint 2 for the equivalent linkage.

The plot of Force vs Crank angle is given in Fig-22 to Fig-23. The maximum force at joint 1 to 4 is 5.883, 4.9967, 4.0788 and 4.9696 respectively. Similarly the joint forces are obtained for set of equivalent mechanism and the results are tabulated in table-11 and table-12 for constant angular crank speed of 5 rpm and 1500 rpm respectively.

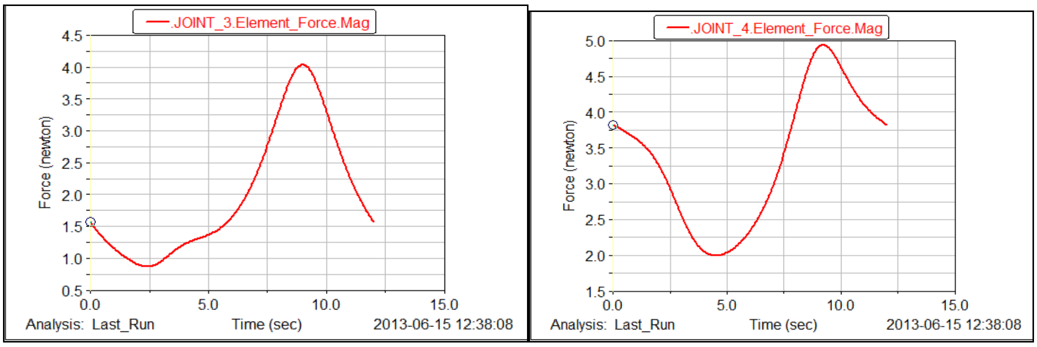

Fig-23: Element force at Joint 2 for the equivalent linkage.

The variations of joint forces for constant crank speed of 5 rpm are shown in fig-24 and for constant crank speed of 1500 rpm are shown in fig-25. Percentage contribution of three clearance joints on the joint forces is 1.68%, 1.98%, 3.33% and 2.19% on joint-1 to joint-4 respectively, for constant crank speed of 5 rpm. For higher crank speed of 1500 rpm it is 0.58%, 0.61%, 8.88% and 7.67%. An obtained result shows that the influence of clearance joints on joint forces is much higher on joint-3, i.e. the joint between coupler and follower, which degrades the performance of the mechanism.

Table-11 Variation of joint forces of four bar mechanism (5 rpm crank speed)

Position	Variation Max Joint Force (N)			
	Joint 1	Joint 2	Joint 3	Joint 4
Ideal	5.8835	4.9895	4.0722	4.9639
Four Bar Mechanism with Clearance at Revolute Joint				
0	5.878	4.9804	4.0613	4.9538
30	5.9092	5.0101	4.1043	4.9907
60	5.9782	5.0883	4.2081	5.073
90	5.9242	5.0403	4.1306	5.0172
120	5.8838	5.0008	4.079	4.964
150	5.8743	4.9893	4.0704	4.958
180	5.8723	4.9819	4.0663	4.9565
210	5.871	4.9742	4.0617	4.9548
240	5.8774	4.9832	4.0692	4.9657
270	5.8622	4.9718	4.0407	4.9409
300	5.8547	4.9693	4.0413	4.936
330	5.8624	4.9703	4.0458	4.9406
360	5.8919	4.9979	4.0845	4.9736
MAX	5.9782	5.0883	4.2081	5.073
MIN	5.8547	4.9693	4.0407	4.936

Table-12 Variation of joint forces of four bar mechanism (1500 rpm crank speed)

Position	**Variation in Max Joint Force (N)**			
	Joint 1	**Joint 2**	**Joint 3**	**Joint 4**
Ideal	**1799.1295**	**1601.3667**	**857.059**	**759.2509**
Four Bar Mechanism with Clearance at Revolute Joint				
0	1804.1845	1605.7674	851.6536	754.1093
30	1805.7451	1605.8271	877.3989	771.3577
60	1809.5545	1611.0951	933.2058	818.2397
90	1799.61	1604.2774	901.3681	789.2088
120	1796.466	1600.9672	874.0738	766.4856
150	1790.5237	1594.7603	863.5318	760.8915
180	1786.1031	1589.7507	854.2343	756.3564
210	1781.1748	1584.2066	854.5181	750.0616
240	1779.6296	1587.3277	865.8128	751.1685
270	1786.5596	1592.923	857.1999	747.0578
300	1792.1692	1597.0943	853.0632	747.5298
330	1797.8393	1601.1701	849.8643	748.6411
360	1803.0574	1604.6875	863.1448	765.631
Max	1809.5545	1611.0951	933.2058	818.2397
Min	1779.6296	1584.2066	849.8643	747.0578

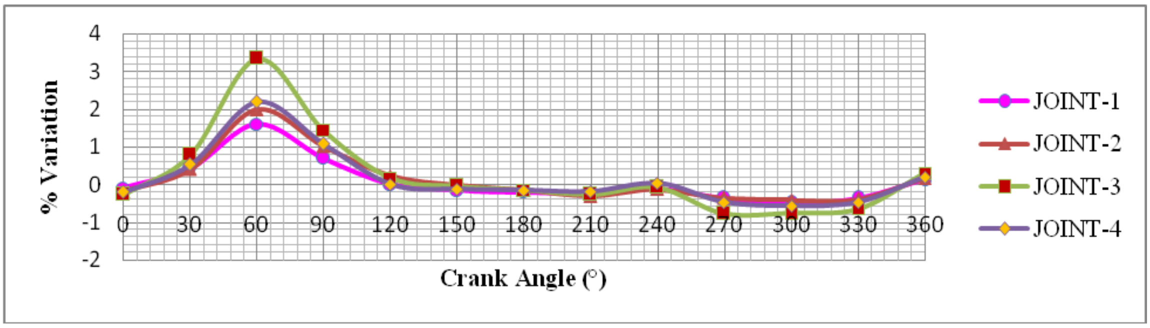

Fig-24: Percentage variation of maximum joint force (5 rpm crank speed)

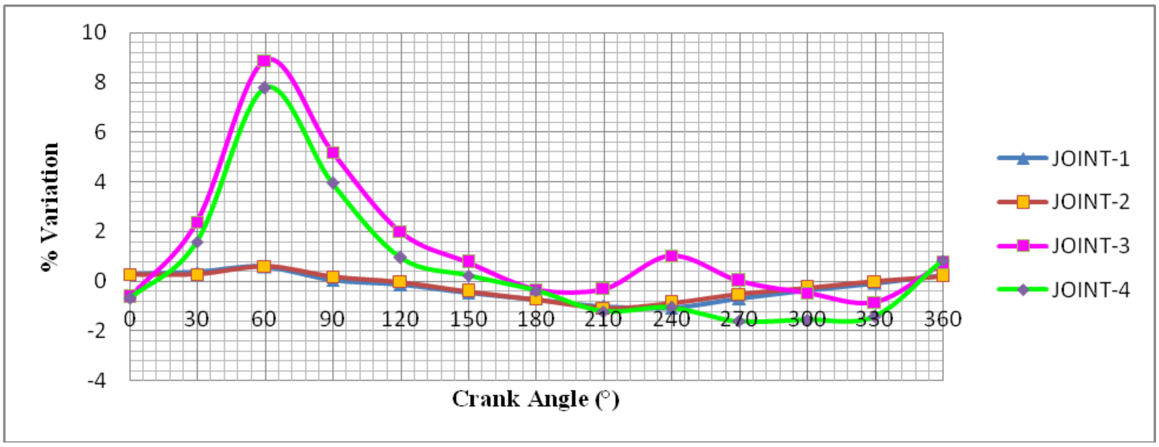

Fig-25: Percentage variation of maximum joint force (1500 rpm crank speed)

V. Conclusion

Presence of clearance in the joint leads to instantaneous change in the point of contact between pin and hole at each joint. A four bar mechanism was simulated with the three clearance joints. Surface contact is considered at each joint. Radial clearance (0.5 mm) at each joint forms a clearance link which is considered as mass-less link. Equivalent linkage was developed by virtue of clearance link causes variations in the link length which are 0.76 % for crank, 0.53 % for coupler and 0.12 % for follower link. Similarly, variation in max angular velocity of coupler is 1.59% for constant crank speed of 5 rpm and variation in max angular velocity of joint-3 is 1.44% for constant crank speed of 5 rpm.

Variations were investigated for higher crank speed of 1500 rpm. Angular velocity of coupler considering joint clearance is 1.57% for constant crank speed of 1500 rpm and max angular velocity of Joint-3 considering joint clearance is 1.42%. Considering pure contact, there is an effect of joint clearance on slower speed mechanism also. Contribution of joint forces on the mechanism varies from 3.334 % to 8.882 % for slower speed mechanism and higher speed mechanism which degrades the performance of mechanism.

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