

Variations in Geometry, Volume, Mass and Moment of Inertia of Link of a Four Bar Mechanism Made of Neat Resin Under Hygrothermal Environment

Shailendra Singh¹, S. Sanyal²

Ph.D. Research Scholar, Department of Mechanical Engineering, N.I.T. Raipur, (C.G.), India and Head of The

Department of Mechanical Engineering, Government Polytechnic College Kanker, (C.G.), India¹Professor and Dean (Research and consultancy), Department of Mechanical Engineering, N.I.T. Raipur, (C.G.), India²

ABSTRACT : Nowadays, Links of a planar and spatial mechanism and Robotic arms are fabricated from Composite materials instead of conventionally used metals(steel and aluminium) with higher specific strength and specific stiffness and contains less weight, thus less inertia forces, stresses, deflections, vibrations of links and mechanism. Mechanisms are also very often used in extreme atmospheric conditions with the requirement of high accuracy and precision especially in aeronautical, aerospace and marine applications. Objective of this work is to investigate and evaluate the variations in volume, mass and moment of inertia of link of a four bar Grashof Type I, Crank-Rocker mechanism made of polymer matrix material (neat Resin) under hygrothermal environment. Chamis proposed the empirical equation for estimating the hygrothermal effect on the matrix properties popularly known as Chamis equation is used here to find out various property degradation of matrix(resin) and composite material. Due to absorption of moisture volume, mass and moment of inertia will enhance thus kinematics and dynamics of mechanism will alter. It is evident that under hygrothermal environment due to enhancement in mass and moment of inertia more stresses and deflection will be observed. Also angular, geometrical and structural variations are evaluated using, Freudenstein's equation. It is found that when a four bar mechanism made of neat resin is working in hygrothermal environment, due to absorption of moisture, link swells and due to elevated temperature thermal expansion takes place, collective effect is increase in overall dimensions of link. It is found that in hygrothermal environment presence of moisture and high temperature affects kinematics and motion characteristic of four bar mechanism, it adversely affects kinematic accuracy and precision of mechanism, thus mechanism will malfunction. So, it is obligatory that effect of hygrothermal atmosphere should be taken into consideration while analyzing kinematic performance or designing the planar mechanism for specific objective. This erroneous behaviour of mechanism can be rectified by estimating exact magnitude of variations under hygrothermal environment and compensating it by accordingly shortening overall dimension of each link i.e. crank, coupler and rocker.

KEYWORDS: Freudenstein's equation, Fickian diffusion, Chamis Equation, Hygrothermal effect, kinematic variations, polymer matrix material, epoxy resin, specific strength, specific stiffness.

NOMENCLATURE: a, b, c, d: lengths of crank, coupler, rocker and fixed/frame link (in mm). a_1 , b_1 , c_1 , d_1 : Enhanced lengths of crank, coupler, rocker and fixed/frame link under hygrothermal environment (in mm). D: Diffusion coefficient ($\text{mm}^2/\text{second}$). J_x : Moisture flux ($\text{mol}/\text{mm}^2\text{-sec}$). L: Length in dry atmosphere when $\Delta T=0$ (in mm). ΔL : Change in length under hygrothermal environment (in mm). m: Moisture content (%). Δm : Enhancement in moisture content from dry condition (%). t: Time (in seconds). ΔT : Enhancement in temperature (in $^\circ\text{C}$). ω_a , ω_b , ω_c : Angular velocity of crank, coupler, rocker (in radian/second). ω_{a1} , ω_{b1} , ω_{c1} : Angular velocity of crank, coupler and rocker under hygrothermal environment (in radian/second). α : Coefficient of thermal expansion ($\text{mm}/^\circ\text{C}$). β , β_L , β_T : Coefficient of moisture expansion in longitudinal and transverse direction in ($\text{mm}/\% \text{moisture absorption}$). ϵ , ϵ_{hygro} , $\epsilon_{\text{thermal}}$: Strain, strain due to hygro (moist) environment, strain due to elevated temperature in (mm/mm) Θ_2 , Θ_3 and Θ_4 : Angular displacement of crank, coupler, and rocker links of four bar kinematic mechanism (in degree). Θ_{31} ,

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Θ_{41} : Angular displacement of coupler and rocker links of four bar kinematic mechanism under hygrothermal environment (in degrees). μ : Transmission angle i.e. angle between coupler and rocker (in degrees, Refer figure 2). γ : Angle between line joining coupler point with pin joining crank to coupler and coupler link(in degrees, Refer fig. 2). P_{wT} =Matrix property at the use temperature T and moisture content M, P_o =Matrix property at reference temperature. T_{gd} = Glass Transition temperature in the dry condition., T_{gw} =Glass Transition temperature in the wet condition.

I. INTRODUCTION

In order to increase the productivity, high speed linkages can be manufactured with composite materials possessing high strength to weight ratio (specific strength) and high stiffness to weight ratio (specific stiffness) compared to conventional material like steel, Aluminium or alloys. Observable fact of hygrothermal environment associated with composite materials was recognised during the mid 1970's. Combination of high humidity and high temperature atmosphere causes a detrimental effect on overall performance of composite-materials. Hygrothermal effect involves entrapment of moisture in the polymer matrix and attained weight increase and more significantly swelling of matrix. Hygrothermal environment is one such environment where presence of moisture and high temperature may alter the geometry and dynamics of mechanisms made of polymer material.

In the present work, analysis of different Grashof four bar planar mechanisms (Crank –Rocker type) made of neat polymer matrix material (epoxy resin), is carried out to find out the variations in volume, mass and moment of inertia of link of a four bar mechanism due to enhanced temperature and humidity i.e. hygrothermal environment. Here computational analysis has been done to find out the variations in volume, mass, moment of inertia of three movable links i.e. Crank coupler and rocker which will affect the overall kinematics and dynamics of mechanism. Chamis proposed the empirical equation for estimating the hygrothermal effect on the matrix properties popularly known as Chamis equation is used here to find out various property degradation of matrix (resin) and composite material. Due to absorption of moisture volume, mass and moment of inertia will enhance thus kinematics and dynamics of mechanism will alter. It is evident that under hygrothermal environment due to enhancement in mass and moment of inertia more stresses and deflection will be observed. Results obtained for the three neat epoxy resins were compared. In order to increase the productivity high speed linkages can be manufactured with composite material which possess high strength to weight ratio and high stiffness to weight ratio compared to conventional material like steel, Aluminium or alloys [1,2,3,4].

The physical phenomenon of hygrothermal effect associated with polymer matrix composites was recognised during the mid 1970's. Combination of high temperature and high humidity environment causes a doubly deleterious effect on structural performance of composites. The two fold problem involves entrapment of moisture in the polymer matrix and attendant weight increase ($\leq 2\%$) and more importantly swelling of matrix. Analysis of moisture absorption data for epoxy or matrix shows that the moisture concentration increases initially with time and approaches an equilibrium (saturation) level after several days or sometimes several months of exposure to humid environment.[5, 6, 7 and 8]. Chamis [10] proposed the empirical equation for estimating the hygrothermal effect on the matrix properties popularly known as Chamis equation is used here to find out various property degradation of matrix (resin) and composite material.

II. RELATED WORK

Thompson et al [1-4] proposed an alternate philosophy by designing mechanism component using fiber reinforced composite materials possessing high specific strength and high specific stiffness. Weight saving upto 70% and good fatigue life and high damping 30 times greater than aluminium is an added advantage of using composite material for mechanism elements. Composite materials can be tailor made with little material wastage. Xianmin Zhang and Wenfeng Zhang [28] has published a paper and claimed that deformation and stresses are produced not alone by mechanical forces but by temperature variations as well. Li et al [29] analyzed large thermal deflections of a Timoshenko beam subjected to transversely non uniform temperature rise by using the shooting method. The physical phenomenon of hygrothermal effect associated with polymer matrix composites was recognised during the mid 1970's. Combination of high temperature and high humidity environment causes a doubly deleterious effect on structural

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III. HYGROTHERMAL EFFECT

Epoxy resin absorbs moisture when exposed to humid atmosphere, initially by instantaneous surface absorption and subsequent diffusion through the interior. The absorbed water is not liquid, but exist in hydrogen bonded molecules or clusters within the polymer. Liquid water may however be transported by capillary action along cracks and in composites along fiber matrix interfaces and may appear at interior voids. The absorbed water softens epoxy resins, cause them to swell and lowers their Glass transition temperature[7,8].In the classical linear diffusion model moisture flux J_x is assumed to be directly proportional to the concentration gradient as given in equation (1).

$$J_x = -D \frac{dM}{dX} \quad \text{(Fick's first law of diffusion) (1)}$$

$$\frac{dM}{dt} = D \frac{d^2M}{dt^2} \quad \text{(Fick's second law of diffusion) (2)}$$

where

$$M = \frac{W - W_d}{W_d} \times 100 \quad \text{..... (3)}$$

Where W is the weight of moist material and W_d is the weight of dry material. M_m is the maximum moisture content. Where M' is the moisture concentration wt. percentage at (x,t) and 'D' is the coefficient of diffusion. Moisture absorption is a function of temperature and time. At higher temperature rate of moisture absorption will be higher. Hygrothermal effect is a twofold problem involves the combination of high temperature and high humidity results in the entrapment of moisture in polymer matrix with the attainment weight increase ($\leq 2\%$) and more importantly a swelling of the matrix. Moisture absorption is a function of temperature and time. At higher temperature, rate of moisture absorption will be higher. It is established that the ingestion of moisture varied linearly with the swelling reported as hygrothermal strain i.e. ϵ_{hygro} .

$$\epsilon_{hygro} = \frac{\Delta L}{L} = \beta \cdot \Delta m \quad \text{..... (4)}$$

Where Δm is the increase from zero moisture (dry condition) and β is the coefficient of moisture expansion. Coefficient of moisture expansion can also be calculated in a composite material as per Schapery's equation and applying Rule of mixture [4].

Along fiber direction
$$\beta_L = \frac{E_m \cdot V_m \cdot \beta_m}{E_m \cdot V_m + E_f \cdot V_f} \quad \text{..... (5)}$$

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& along transverse direction $\beta_T = \beta_m V_m (1 + V_m)$ (6)

Due to elevated temperature, length of the bar will increase and thermal strain.

$$\epsilon_{thermal} = \frac{\Delta L}{L} = \alpha \cdot \Delta T$$
 (7)

here, ΔL = Change in length due to elevated temperature, ΔT = Change in temperature, L = Original Length. The total strain due to hygro and thermal environment

$$\epsilon = \epsilon_{hygro} + \epsilon_{thermal}$$
 (8)

Chamis et al. [10] proposed the following empirical equation for estimating the hygrothermal effect on the matrix properties. This can subsequently be used in modifying the matrix-dominated properties of a unidirectional lamina. The equations for predicting, hygrothermal degradation effects in composites using micromechanics are summarized in equation no. 9 and 10. Note also that the effects on the thermal properties are the reciprocal of those on the mechanical properties. It is worth noting that the equations no. 9 is obtained by curve fitting experimental data.

$$\frac{P_{wT}}{P_o} = \left[\frac{T_{gd} - T}{T_{gd} - T_o} \right]^{1/2}$$
 (9)

Here, P_{wT} = Matrix property at the use temperature T and moisture content M , P_o = Matrix property at reference temperature. T_{gd} = Glass Transition temperature in the dry condition., T_{gw} = Glass Transition temperature in the wet condition with a moisture content M The Glass transition temperature in wet condition, T_{gw} is calculated using the following equation

$$T_{gw} = (0.005 \times M^2 - 0.1 \times M + 1) \times T_{gd} \text{ for } M < 10\%$$
 (10)

The material for the present analysis of of the mechanism is taken as polymer matrix material neat resin system R914, 3502, 8551-7.

Table1: Properties degradation of Carbon Epoxy (8551-7) composite material

Properties of carbon Epoxy composite material	Normal Environment	Hygrotherml Environment (as per chamis equation)	Percentage variation (%)
Density(gm/cm3)	1.58	1.608	1.77
Longitudinal Young's Modulus(GPa)	133.38	132.705	0.5
Transverse Young's Modulus(GPa)	8.29	5.459	34
Longitudinal Shear Modulus(MPa)	3.81	2.322	39
Transverse Shear Modulus(MPa)	2.90	1.949	32.8
Longitudinal Poisson's Ratio	0.24	0.192	20
Transverse Poisson's Ratio	0.424	0.4	5.66

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Table2: Properties degradation of Kelvar/Epoxy (3502) composite material

Properties of Kelvar Epoxy composite material	Normal Environment	Hygrotherml Environment (as per chamis equation)	Percentage variation (%)
Density(gm/cm ³)	1.4	1.428	2.0
Longitudinal Young's Modulus(GPa)	91.38	90.745	0.695
Transverse Young's Modulus(GPa)	4	3.274	18.15
Longitudinal Shear Modulus(MPa)	2.26	1.686	25.4
Transverse Shear Modulus(MPa)	1.44	1.187	17.67
Longitudinal Poisson's Ratio	0.35	0.286	18
Transverse Poisson's Ratio	0.484	0.379	21.69

Table3: Properties degradation of Boron/Polyimide composite material

Properties of Boron polyimide composite material	Normal Environment	Hygrotherml Environment (as per chamis equation)	Percentage variation (%)
Density(gm/cm ³)	2.07	2.100	1.449
Longitudinal Young's Modulus(GPa)	241.38	241	0.157
Transverse Young's Modulus(GPa)	14.87	12.85	13.58
Longitudinal Shear Modulus(MPa)	5.53	4.783	13.50
Transverse Shear Modulus(MPa)	5.53	4.783	13.50
Longitudinal Poisson's Ratio	0.26	0.241	7.308
Transverse Poisson's Ratio	0.394	0.343	12.944

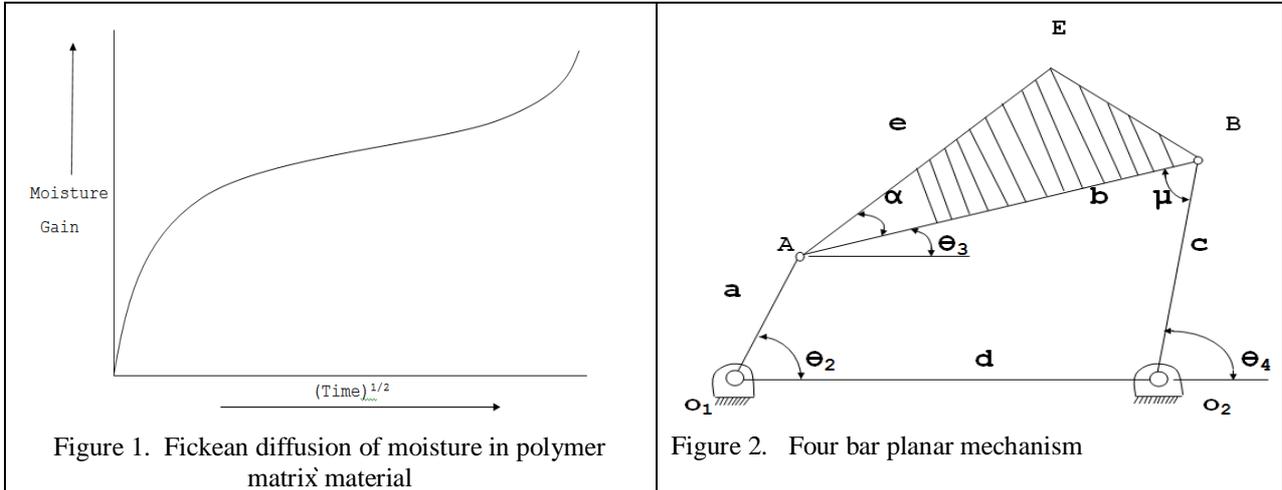
IV. THE VARIATIONS IN THE MASS, VOLUME, MOMENT OF INERTIA OF A LINK OF FOUR BAR MECHANISM UNDER HYGROTHERMAL ENVIRONMENT

Epoxy resin absorbs moisture when exposed to humid atmosphere, initially by immediate surface absorption and subsequently due to diffusion in to the interior. Liquid water may is transported by capillary action along cracks and in composites along fibre matrix interfaces and may appear at interior voids. The absorbed water softens epoxy resins, causes them to swell. In the conventional Fickian linear diffusion model moisture flux is supposed to be directly proportional to the concentration gradient as shown in figure 1. Four bar mechanism and its detailed dimensions are shown in Figure 2

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Polymer matrix materials neat Resin Systems-R914, 3502, 8551-7 are taken as materials for the present analysis of the mechanism. Depending upon individual values of α , β , Δm and ΔT different polymer materials behaves differently. Average material properties of these materials under hygrothermal environment tested at room temperature is taken as following in Table-4 [11] and [12].

Table 4 : Average material (Neat Resin)properties α , β and equilibrium moisture content.

S.No.	Neat Resin System	Moisture Condition	Coefficient of Thermal Expansion (α) ($10^{-6}/^{\circ}\text{C}$)	Coefficient of Moisture Expansion (β) ($10^{-3}/\%M$)	Equilibrium Moisture Content (%M)
1.	R914	Dry Wet	58.4 62.6	3.02	7.0
2.	3502	Dry Wet	50.5 55.5	2.70	5.0
3.	8551-7	Dry Wet	46.7 70.0	3.09	2.0

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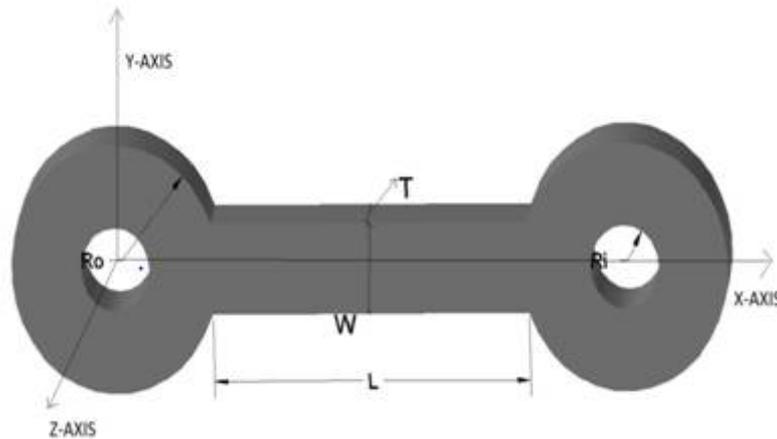


Figure No. 3: Dimensions of a link of a four bar mechanism

Here, dimensions of a link of four bar mechanism is shown in Figure 3. Here L , W , T is the length width and thickness of central prismatic bar respectively. R_o and R_i are radius of round circular hollow ends with same thickness as of central prismatic bar.

Table 5: Expression for volume, mass, moment of inertia of links under dry and hygrothermal environment

S.No.	Details	Expression under dry condition	Expression under Hygrothermal Environment
1.	Volume of Central Prismatic Bar	$W \cdot T \cdot L$	$W_1 \cdot T_1 \cdot L_1$
2.	Mass of Central Prismatic Bar	$M_{bar} = \rho \cdot W \cdot T \cdot L$	$(M_{bar})_1 = \rho_1 \cdot W_1 \cdot T_1 \cdot L_1$
3.	Volume of each Hollow Cylinder	$\pi \cdot (R_o^2 - R_i^2) \cdot T$	$\pi \cdot (R_{o1}^2 - R_{i1}^2) \cdot T_1$
4.	Mass of each Hollow Cylinder	$M_{cyl} = \pi \cdot (R_o^2 - R_i^2) \cdot T$	$(M_{cyl})_1 = \pi \cdot (R_{o1}^2 - R_{i1}^2) \cdot T_1$
5.	Mass Moment of Inertia of Central Prismatic Bar	$I_{bar} = M_{bar} \cdot (W^2 + T^2) / 12$	$(I_{bar})_1 = (M_{bar})_1 \cdot (W_1^2 + T_1^2) / 12$
6.	Mass Moment of Inertia of each hollow cylinder	$I_{cyl} = M_{cyl} \cdot (R_o^2 + R_i^2) / 2$	$(I_{cyl})_1 = (M_{cyl})_1 \cdot (R_{o1}^2 + R_{i1}^2) / 2$
7.	Mass Moment of Inertia about Z-Axis	$I_{cyl} + [I_{bar} + M_{bar} \cdot (D_{bar})^2] + I_{cyl} + M_{cyl}$	$(I_{cyl})_1 + [I_{bar1} + M_{bar1} \cdot (D_{bar1})^2] + (I_{cyl})_1 + M_{cyl1}$

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Table 6: Variation in volume, mass, moment of inertia of links under hygrothermal environment

S · N o ·	Link Length (mm)	Material of link	Volume of link (mm ³)		Mass of Link(gram)		Mass Moment of Inertia of Link about centre of gravity(gram-mm ²)	
			Dry	Hygrotherm al	Dry	Hygrothermal	Dry	Hygrothermal
1	a=100	R-914	73699	79991	147	158	7132765	8622622
2	a=100	3502	73699	77938	147	154	7132765	8161202
3	a=100	8551-7	73699	76577	147	150	7132765	7612314
4	a=1000	R-914	61369 9	667456	1227	1313	710755166	860584074
5	a=1000	3502	61369 9	649004	1227	1289	710755166	813372280
6	a=1000	8551-7	61369 9	637662	1227	1252	710755166	758593142
7	b=c=d=1200	R-914	73369 9	796339	1467	1570	1023450234	1171745656
8	b=c=d=1200	3502	73369 9	775908	1467	1540	1023450234	1171215532
9	b=c=d=1200	8551-7	73369 9	762348	1467	1496	1023450234	1092335194

V. SIMULATION AND RESULT OF KINEMATIC VARIATIONS UNDER HYGROTHERMAL ENVIRONMENT

In general, objective of a mechanism is to provide a constrained motion for a specific purpose. In the present work, an analysis has been carried out to determine the variations in geometry a planar four bar mechanism made of neat polymer matrix material (epoxy resin), subjected to hygrothermal environment. Three neat epoxy resins are considered as material of four bar mechanism viz. R-914, 3502 and 8551-7. Kinematic variation analysis is carried out to find out structural and angular variations[13,14].

(A) STRUCTURAL VARIATIONS

Due to hygrothermal environment the link lengths change causing structural variations. Change in length of link ΔL_T due to temperature enhancement is given by.

$$\Delta L_T = L.\alpha.\Delta T \quad \dots\dots\dots (11)$$

Similarly, change in link length due to humid (hygro) environment, ΔL_h is given by.

$$\Delta L_h = L.\beta.\Delta m \quad \dots\dots\dots (12)$$

Where, β =Coefficient of moisture expansion, Δm = moisture absorbed by link.Total change in length of every link is thus

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$$\Delta L = L(\alpha.\Delta T + \beta.\Delta m) \dots\dots\dots (13)$$

Let, in dry atmosphere and at room temperature, the length of crank is 'a', coupler is 'b' and rocker is 'c' and length of fixed link is 'd' as shown in fig. 2. Let the mechanism is made of a neat polymer matrix material. Then, the length of various links of four bar planar mechanism made of polymer material will change to the new enhanced length under hygrothermal environment. Viz. are

Crank	$a_1 = a (\alpha.\Delta T + \beta.\Delta m)$	}	(14)
Coupler	$b_1 = b (\alpha.\Delta T + \beta.\Delta m)$		
Rocker	$c_1 = c (\alpha.\Delta T + \beta.\Delta m)$		
Fixed link	$d_1 = d (\alpha.\Delta T + \beta.\Delta m)$ If fixed link is made of FRPC material.		
Fixed link	$d_1 = d (\alpha.\Delta T)$, made of metal		

Due to variation in link lengths, co-ordinates of centre of pin of joint connecting Crank with Coupler i.e. point A is ($A_x = a.\cos\theta_2$, $A_y = a.\sin\theta_2$) will alter in hygrothermal environment as $A_{x1} = a_1.\cos\theta_2$ and $A_{y1} = a_1.\sin\theta_2$. Similarly coordinate of hinged joint connecting coupler with rocker viz. $B_x = a.\cos\theta_2 + b.\cos\theta_3$ and $B_y = a.\sin\theta_2 + b.\sin\theta_3$ will alter to coordinates $B_{x1} = a_1.\cos\theta_2 + b_1.\cos\theta_{31}$ and $B_{y1} = a_1.\sin\theta_2 + b_1.\sin\theta_{31}$ in hygrothermal environment. A and B are also located at the extreme ends of Coupler their path is generated for one complete rotation of Crank, under hygrothermal environment [15] and shown in Figure No 4 and 5, for neat resin material 3502 and R-914. Here, Point A is centre of pin connecting Crank and Coupler, its locus is shown in Figure 4. Point B, is centre of pin connecting Coupler with Rocker, its locus is shown in Figure 5.

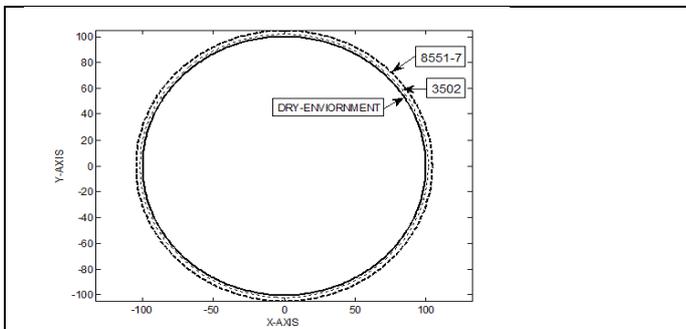


Figure 4. Trajectory traced by centre point –A under hygrothermal environment for different materials viz. R-914, 3502 and link lengths a=100mm, d=200mm, b=c=160mm, Δm=7%, Δt=95°C.

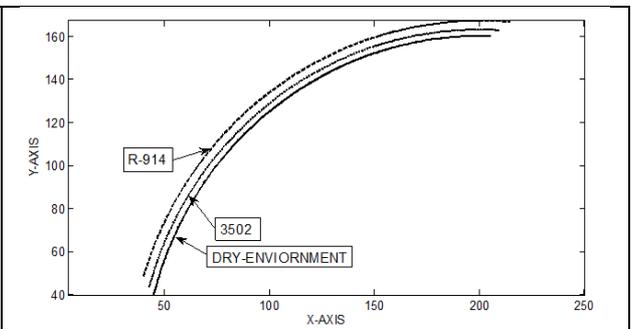


Figure 5. Trajectory traced by point-B under hygrothermal environment for different materials viz. R-914, 3502 and link lengths (a=100mm, d=200mm, b=c=160mm), Δm=7%, Δt=95°C.

(B) ANGULAR VARIATIONS

Angular displacement θ_i of mechanism depends mainly on link lengths. Any change in link length due to hygrothermal environment will cause variations in angular position. Here position analysis is carried out to find out alteration in θ_3 , θ_4 and transmission angle ' μ ' with respect to θ_2 for 360° rotation of crank under hygrothermal environment. Here, simulative analysis is done considering that crank, coupler and rocker is made of polymer and fixed link is made of metal.

Variations in angle θ_3 with respect to θ_2 :

The angle θ_3 in the mechanism is given by Freudenstein's equation [16, 17, 18, 19, 20, 21] in terms of link lengths a, b, c, d and input angle θ_2 .

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$$\theta_3 = 2 \tan^{-1} \left[\frac{-E \pm \sqrt{E^2 - 4DF}}{2D} \right] \dots\dots\dots (15)$$

where, $K = (a^2 - b^2 + c^2 + d^2)$, $D = K - a.(d + b).Cos\theta_2 + b.d$, $E = 2.a.b \text{ Sin}\theta_2$, $F = K - a.(d - b).Cos \theta_2 + b.d$

In the hygrothermal environment θ_3 will change to θ_{31} , as following

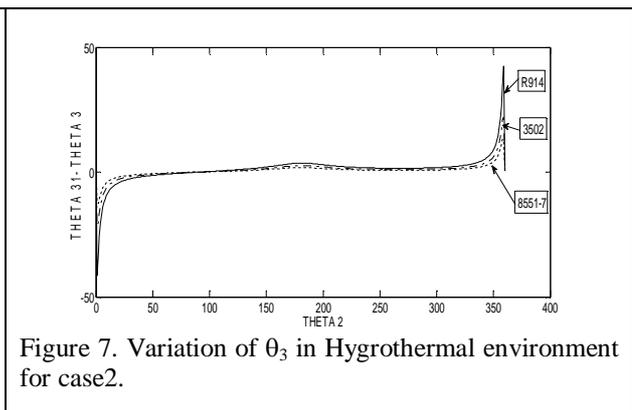
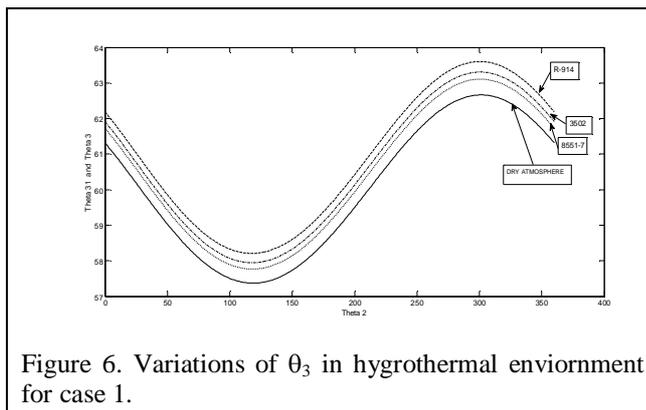
$$\theta_{31} = 2Tan^{-1} \left[\frac{-E_1 \pm \sqrt{E_1^2 - 4D_1F_1}}{2D_1} \right] \dots\dots\dots (16)$$

Where, $K_1 = (a_1^2 - b_1^2 + c_1^2 + d_1^2)$, $D_1 = K_1 - a_1 (d_1 + b_1) Cos\theta_2 + b_1d_1$, $E_1 = 2a_1 b_1 Sin\theta_2$, $F_1 = K_1 - a_1 (d_1 - b_1) Cos \theta_2 + b_1d_1$

Results are determined and plotted in the form of variations in angle θ_3 for complete rotation of crank angle i.e. θ_2 in Figure no. 6 and 7. Two extreme cases with different combination of grasshof mechanisms are considered for evaluating the effect of hygrothermal environment. Two, extreme cases are analysed. Enhancement in moisture content due to hygrothermal environment is taken as maximum moisture absorption as given in Table1 & enhancement in temperature is taken as $\Delta t=95^\circ C$

Case1: Here different link lengths are taken as $a=5mm$, $b=125mm$, $c=125mm$, $d=120mm$ and materials for this Grashof mechanism are taken as R914, 3502 & 8551-7 neat resin. Variations of θ_3 in hygrothermal environment for different materials for complete rotation (0° to 360°) of crank is shown in Figure 6.

Case2: Here, we have taken different link lengths as $a=115mm$, $b=c= d=120mm$ and material of this Grasof mechanism is R914, 3502 & 8551-7 neat resin. Absolute variation of θ_3 in hygrothermal environment i.e. $(\theta_{31}-\theta_3)$ for different materials for complete rotation (0° to 360°) of crank is shown in Figure 7.



Variation in output angle θ_4 with respect to θ_2 :

Output angle θ_4 can be determined by Freudenstein’s equation [22, 23, 24, 25, 26 and 27] for every input angle θ_2 as per the following.

$$\theta_4 = 2 \tan^{-1} \left[\frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \right] \dots\dots\dots (17)$$

$A = K - a (d - c) Cos\theta_2 - cd$, $B = -2ac Sin\theta_2$, $C = K - a (d + c) Cos \theta_2 + cd$, $K = (a^2 - b^2 + c^2 + d^2)/2$

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Now due to hygrothermal environment θ_4 will change to θ_{41} and the angle

$$\theta_{41} = 2 \tan^{-1} \left[\frac{-B_1 \pm \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \right] \dots\dots\dots (18)$$

$$A_1 = K_1 - a_1 \cdot (d_1 - c_1) \cdot \cos \theta_2 - c_1 d_1, \quad B_1 = -2a_1 c_1 \cdot \sin \theta, \quad C_1 = K_1 - a_1 \cdot (d_1 + c_1) \cdot \cos \theta_2 + c_1 d_1,$$

$$K_1 = (a_1^2 - b_1^2 + c_1^2 + d_1^2) / 2$$

Variations in output angle under hygrothermal environment for three materials are obtained and plotted in figure no.8 and Figure no. 9. Two, extreme cases are analysed.

Case1: Here, variations in θ_4 with respect to θ_2 for complete rotation of Crank, are determined and presented in figure8. Here, we have taken different link lengths as $a=5\text{mm}$, $b=c=d=125\text{mm}$ and materials for this Grashof mechanism are R914, 3502 & 8551-7 neat resin .Enhancement in moisture content due to hygrothermal environment is taken as maximum moisture absorption as given in Table1 & enhancement in temperature is taken as $\Delta t=95^\circ\text{C}$.

Case2: Here, variation in θ_4 for complete rotation of Crank, are determined and presented. We have taken different link lengths as $a=115\text{mm}$, $b=c= d=120\text{mm}$ and material of this Grashof mechanism is R914, 3502 & 8551-7 neat resin. Other conditions are same as case1. Here, variations in θ_4 with respect to θ_2 for complete rotation of Crank, are determined and presented in Figure 9.

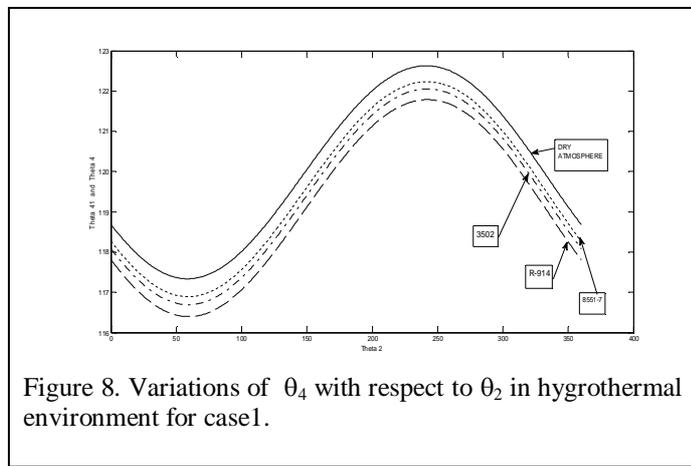


Figure 8. Variations of θ_4 with respect to θ_2 in hygrothermal environment for case1.

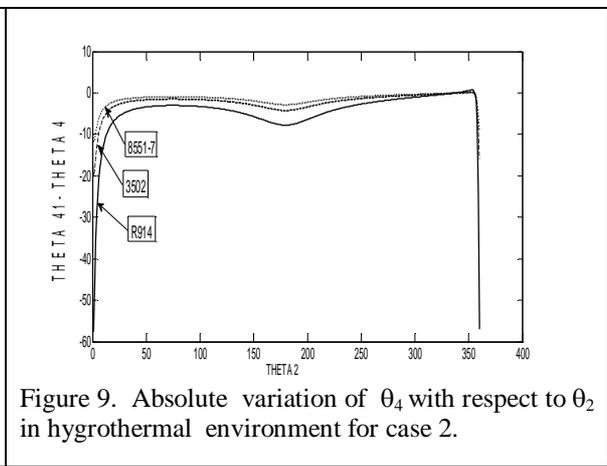


Figure 9. Absolute variation of θ_4 with respect to θ_2 in hygrothermal environment for case 2.

VI. CONCLUSION

Here, three neat epoxy resins were considered as material of links of four bar mechanism viz. R-914, 3502, and 8551-7. Results obtained for the three neat epoxy resins were compared. The maximum geometrical variations under hygrothermal environment were observed for R-914, as maximum moisture is absorbed by this epoxy resin so more swelling and more change in length of link thus higher structural and angular variations are observed. Due to absorption of moisture volume will enhance and density and mass will also increase thus mass moment of inertia of each link of four bar chain will increase. Maximum variation in mass, volume and moment of inertia are observed for link made of R-914 resin. Average enhancement in mass of link is 4.68 percent. Average enhancement in moment of inertia of link is 6.56 percent. Maximum enhancement under hygrothermal environment in moment of inertia is observed for link made of R-914 is 21 percent with reference to dry atmosphere. Due to absorption of moisture volume, mass and moment of inertia will enhance thus kinematics and dynamics of mechanism will alter. It is evident that under hygrothermal environment due to enhancement in mass and moment of inertia more stresses and deflection will be observed. As kinematics and dynamics will also be affected thus accuracy and precision of mechanism will be

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adversely altered. So it is obligatory that this should be considered while designing a mechanism subjected to hygrothermal environment.

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