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Deviations in coupler curve due to hygrothermal environment in four bar planar mechanism made of neat resin

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ABSTRACT

Demand for higher production rate compels to operate machines at ever increasing speeds. With the advent of new manufacturing technologies now machine parts and mechanisms are also made of composite materials having high strength to weight ratio and high stiffness to weight ratio instead of homogeneous & isotropic materials such as carbon steels or aluminum metals. So, the members(Links) can also be fabricated from F.R.P.C. (fiber reinforced polymer composites) or simple P.M.M. (polymer matrix material) for very high speed of operations, this also result in weight savings up to 70%, thus less inertia forces , stresses, deflection, noise and vibration of links, therefore less chances of fatigue failure. These mechanisms are very often used in extreme atmospheric conditions with the requirement of high accuracy. In hygrothermal environment presence of moisture & high temperature affects the kinematic accuracy & precision of mechanism, also deviations in coupler curves are observed. In the present work F.R.O.M.(Full-Range-Of-Motion) computational simulative analysis has been done to find out the kinematic deviations mainly with reference to coupler curve of four bar mechanism made of neat polymer matrix material(Neat Resin)i.e. R-914 and 8551-7, when they are subjected to high temperature and high humidity environment i.e. hygrothermal environment with reference to dry atmosphere. It is found that due to structural deviations, coupler curve of four bar mechanism is altered under hygrothermal environment.

Keywords:
Freudenstein's equation, Fickean diffusion, Hygrothermal effect, Kinematic deviations, Coupler curve, Polymer matrix material, Full-Range-Of-Motion.

Nomenclature:
(a, b, c, d) and (a_1, b_1, c_1, d_1): Lengths of crank, coupler, rocker and fixed/frame link under dry and hygrothermal environment (in mm). D: Diffusion coefficient (mm²/second).J_x: Moisture flux (mol/mm²-sec), L = Length of Link, ΔT = Change in temperature ΔL: increase in length under hygrothermal environment (in mm). Δm: Enhancement in moisture content from dry condition (%). t: Time (in seconds). ΔT: Enhancement in temperature (˚C). α: Coefficient of thermal expansion (mm / ˚C). β, β_L, β_T: Coefficient of moisture

expansion, Coefficient of moisture expansion in longitudinal and transverse direction in (mm / % of moisture absorption). ε, ε_{hygro}, $\varepsilon_{thermal}$: Strain, strain due to hygro(moist) environment and strain due to elevated temperature in (mm/mm). θ_2: Angular displacement of crank. θ_3, θ_4, θ_{31}, θ_{41}: Angular displacement of coupler and rocker link under dry and hygrothermal environment in degrees. μ: Transmission angle. γ: Angle between line joining coupler point with pin joining crank to coupler and coupler link in degrees.

1. INTRODUCTION

In order to increase the productivity the high speed linkages are manufactured with composite material which posses high strength to weight ratio and high stiffness to weight ratio compare to conventional material used to fabricate the linkages like steel, Aluminum or alloys [1-6; 26]. During the mid 1970's a physical phenomenon associated with polymer matrix composites was recognized know as hygrothermal effect, that is due to combination of high temperature and high humidity caused a doubly deleterious effect on structural performance of composites. The two fold problem involves entrapment of moisture in the polymer matrix and attains dent weight increase and more importantly swelling of matrix. It was realized that the ingestion of moisture varied linearly with the swelling of matrix. In fact the epoxy absorbs the moisture when subjected to high humid atmosphere. In this study analysis of different Grashof four bar planer mechanisms is done to find out the deviations in Geometry of mechanism, output angles and in coupler curve using Freudenstein's equation due to enhanced temperature and humidity.

2. 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 rather 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, causes them to swell and lowers their Glass transition temperature. In the classical linear diffusion model moisture flux is assumed to be directly proportional to the concentration gradient also known as Fickean diffusion (refer fig.1). Therefore the basic equations governing the diffusion into the plate are:

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

and

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

The initial boundary conditions are

$$M(x, 0) = 0 \qquad \text{...... (3)}$$

$$M(\pm l, t) = Mm \qquad \text{...... (4)}$$

Where,

$$\frac{dM}{dt} = \frac{W - W_d}{W_d} \times 100 \qquad \text{...... (5)}$$

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. Jx is the moisture flux, t denotes time. 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 so that in fact

$$\epsilon_{hygro.} = \frac{\Delta L}{L} = \beta.\Delta m \quad \text{……... (6)}$$

Where Δm is the increase from zero moisture (dry condition) measured in percentage weight increase and β is the coefficient of moisture expansion. Coefficient of moisture expansion can also be calculated as per schapery's equation and applying Rule of mixture [7-14].Along fiber direction and along Transverse direction

$$\beta_L = \frac{E_m.V_m.\beta_m}{E_m.V_m + E_f.V_f} \quad \text{..……..... (7)}$$

$$\beta_T = \beta_m V_m (1 + V_m) \quad \text{……...... (8)}$$

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

$$\epsilon_{thermal} = \frac{\Delta L}{L} = \alpha.\Delta T \quad \text{……...... (9)}$$

$$\epsilon = \epsilon_{hygro} + \epsilon_{thermal}$$

Here, in this analysis of four bar mechanism we have assumed that the material of the mechanism is polymer matrix materials i.e. neat resin system R-914 and 8551-7. The average Material properties for Neat Resin Systems R-914, 8551-7, Tested under hygrothermal environment is given below in tabular form [15-16]. Enhancement in moisture is taken as maximum enhancement in moisture gain and enhancement in temperature is taken as 80˚C.

Neat Resin System	Moisture Condition	Coefficient of Thermal Expansion (10^{-6}/°C)	Coefficient of Moisture Expansion (10^{-3}/%M)	Equilibrium Moisture Content (%M)
R-914	Dry Wet	58.4 62.6	3.02	7.0
8551-7	Dry Wet	46.7 70.0	3.09	2.0

3. POSITION ANALYSIS

Position analysis is done to find out alteration in θ_3, θ_4. A four bar mechanism is shown in figure no.2. We have taken a link made of composite material having a length L.

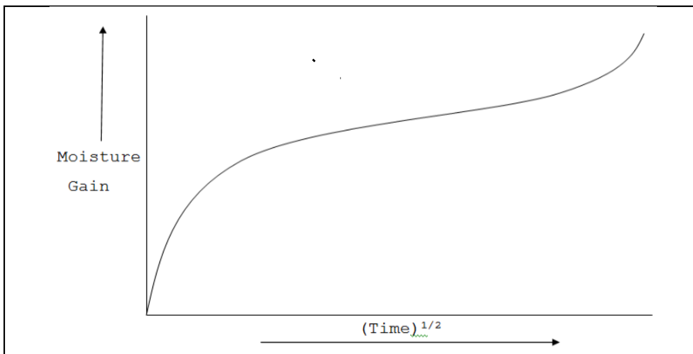

Figure 1. Fickean diffusion of moisture in P.M.M.

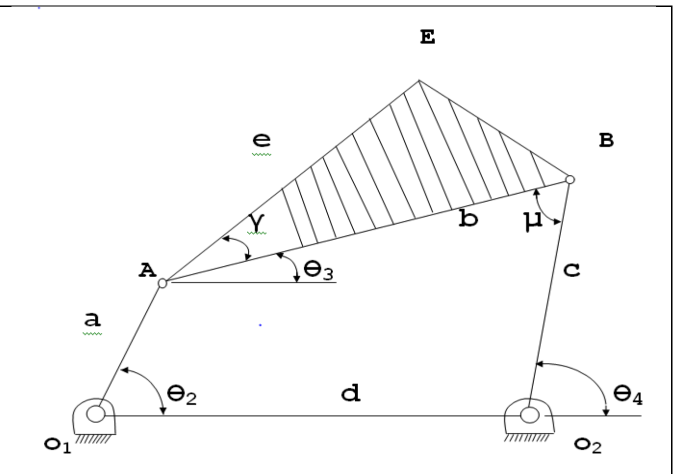

Figure 2. Four bar planar mechanism

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Then change in length of link due to temperature enhancement

$\Delta L_T = L.\alpha.\Delta T$ ……... (10)

Change in Length due to hygro (moist) environment

$\Delta L_h = L.\beta.\Delta m$ ……... (11)

Total Change in Length due to hygrothermal environment

$\Delta L = \Delta L_T + \Delta L_h$

$\Delta L = L (\alpha.\Delta T + \beta.\Delta m)$ ……... (12)

Let the mechanism is made of a neat resin from any of the material given in Table 1. Due to hygrothermal environment the link length will change, so now the enhanced length of Crank $a_1 = a (\alpha.\Delta T + \beta.\Delta m)$, Coupler $b_1 = b (\alpha.\Delta T + \beta.\Delta m)$, Rocker $c_1 = c (\alpha.\Delta T + \beta.\Delta m)$, assumed that fixed link is made of metal, so $d_1 = d.\alpha.\Delta T$. Position analysis is done for this problem using Freudenstein's equation [28].

$$\theta_4 = 2Tan^{-1}\left[\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right] , \qquad \theta_3 = 2Tan^{-1}\left[\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right]$$

here, A = K – a (d - c) Cosθ2 – c.d , B = -2ac Sinθ, C = K – a (d + c) Cos θ + c.d, K = (a2 – b2 + c2 + d2)/2 ,D = K – a (d + b) Cosθ2 + b.d, E = 2ab Sinθ2, F = K – a (d - b) Cos θ2 + b.d

Now due to hygrothermal environment θ_3 and θ_4 will change, let now θ_3 is θ3' and θ_4 is

$$\theta_3' = 2Tan^{-1}\left[\frac{-E_1 \pm \sqrt{E_1^2 - 4D_1F_1}}{2D_1}\right]$$

θ4' $$\theta_4' = 2Tan^{-1}\left[\frac{-B_1 \pm \sqrt{B_1^2 - 4A_1C_1}}{2A_1}\right]$$

$A_1 = K_1 - a_1$ (d1 – c1) $\text{Cos}\theta_2 - c_1d_1$, $B_1 = -2.a_1.c_1.$ Sinθ2, $C_1 = K_1 - a_1 (d_1 + c_1) \text{Cos } \theta_2 + c_1d_1$

$K_1 = (a_1^2 - b_1^2 + c_1^2 + d_1^2)/2$, $D_1 = K_1 - a_1. (d_1 + b_1) \text{Cos}\theta_2 + b_1 .d_1$, $E_1 = 2a_1. b_1.$ Sinθ, $F_1 = K_1 - a_1. (d_1 - b_1) \text{Cos } \theta_2 + b_1 .d_1$ To find out deviation for complete notation of Crank θ_3 and θ_4 are calculated using F.R.O.M.(Full-Range-Of-Motion) simulation for which Code was also generated. Also θ_3' and θ_4' are calculated. Co-ordinate of hinged joint connecting Crank with Coupler is (Ax, Ay) here, $A_x = a.\text{Cos}\theta_2$, $A_y = a.\text{Sin}\theta_2$, New coordinates in hygrothermal environment are $A_{x1} = a_1.\text{Cos}\theta_2$, $A_{y1} = a_1 .\text{Sin}\theta_2$ .Coordinate of hinged joint connecting Coupler with rocker is $B_x = a \text{ Cos}\theta_2 + b \text{ Cos}\theta_3$, $B_y = a \text{ Sin}\theta_2 + b \text{ Sin}\theta_3$ Now, new coordinates in hygrothermal environment are $B_{x1} = a_1 \text{ Cos}\theta_2 + b_1 \text{ Cos}\theta_{31}$, $B_{y1} = a_1.\text{Sin}\theta_2 + b_1.\text{Sin}\theta_{31}$. 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.

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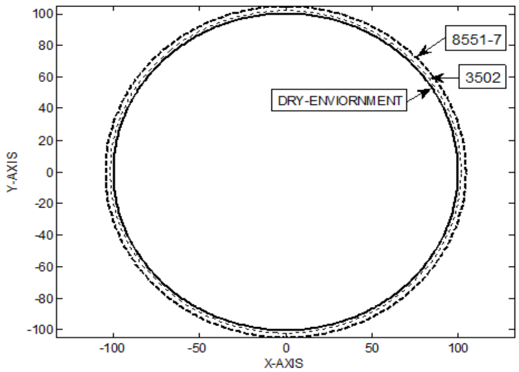

Figure 3. Trajectory traced by centre point –A under hygrothermal environment for different materials viz. R-914, 3502 and link lengths a=100mm, d=200mm, b=c=160mm, Δm=7%, Δt=95˚C.

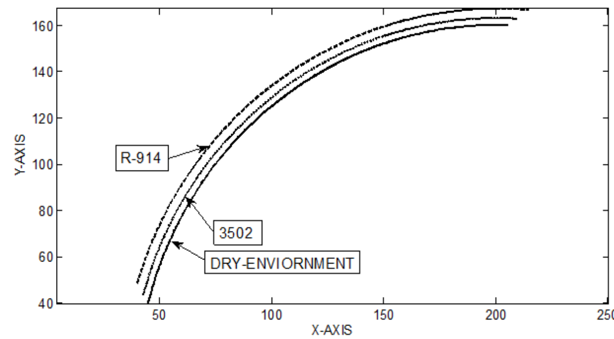

Figure 4. Trajectory traced by point-B under hygrothermal environment for different materials viz. R-914, 3502 and link lengths (a=100mm, d=200mm, b=c=160mm), Δm=7%, Δt=95˚C.

4. DEVIATIONS IN COUPLER CURVE

Coupler curve have been in use in the design of machinery ever since James watt used a straight segment of a lemniscoidal curve for guidance purpose in his double acting Steam engine in 1782. Around the same time (1788) John Fitch made use of the entire curve in designing crank driver paddles at the stern of a boat. In the subsequent decade there was a lot of interest in designing linkages to accomplish specific task mostly in straight line generation .In the middle of nineteenth century the algebraic geometers of that time Cayley [17-18] and Roberts [19-20] shifted focus on to the analytical treatment of Coupler curves. Their studies established many interesting properties of four bar coupler curve including its algebraic equation. Coupler curves are used to generate useful path motions for design problems. They can approximate straight line, circular arc etc. Coupler curve is a solution to a path generation problem. It is a very useful device. The four-bar linkage has a coupler curve equation of degree 6 while slider crank linkage has a coupler curve of degree 4. Horns and Nelson atlas of four-bar coupler curve is useful reference to provide a starting point for design and analysis. It contains 7000 coupler curves and defines the linkage geometry for each of its Grashof's crank-rocker linkages [21]. Basic method of obtaining the equation of coupler for four-bar linkage is briefly presented. A tracing point on coupler link has a coordinates (x, y) obtained by rotating crank of the linkage as shown in Fig.2. The first analytical investigation of coupler curve, the curve of the Watt mechanism was undertaken by Prony, who examined Watt's "straight–line motion" for deviations (1796). Around the same time (1788) John Fitch made use of the entire curve in designing crank driver paddles at the stern of a boat. Subsequently, there was a lot of interest in designing linkages to accomplish specific task using various type of coupler curves, mostly in straight line generation. Almost all of the modern analytical approaches to path generation are either limited to a finite number of points based on the Burmester's theory, or oriented towards approximate path generation through optimization [23-24]

Coupler curves are used to generate useful path motions. They can approximate straight line, circular arc, kidney bean shape, crunodes, cusp, umbrella, triple loop, crescent, pseudo ellipse, scimitar, figure- eight etc [25]. Coupler curve of four bars is an algebraic curve of sixth order, depending on geometry of four bar mechanism and position of coupler point. Coupler curve is function of (a, b, c, d, e, Ψ, α, β, Δt, Δm), but under hygrothermal environment coupler curve is function of (a, b, c, d, e, Ψ, α, β, Δt, Δm, t). Position of coupler point E (offset) having coordinates X_e & Y_e can be expressed as

$X_e = a.\text{Cos}\theta_2 + e.\text{Cos}(\gamma + \theta_3)$, $Y_e = a.\text{Sin}\theta_2 + e.\text{Sin}(\gamma + \theta_3)$. Where, e = AE and $\gamma = \angle EAB$, Fig.2. The coordinates of coupler point will change due to hygrothermal environment. Xe and Ye will have the following value $Xe_1 = a_1.\text{Cos}\theta_2 + e_1.\text{Cos}(\gamma_1 + \theta_{31})$ and $Ye_1 = a_2.\text{Sin}\theta_2 + e_1.\text{Sin}(\gamma_1 + \theta_{31})$.

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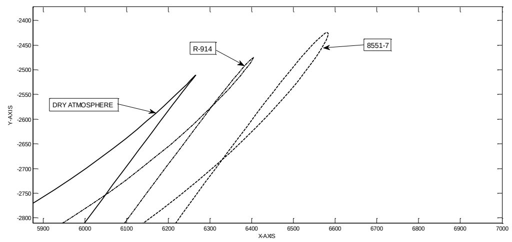

Figure 5 Coupler curve deviations for different material under hygrothermal environment, a=2250mm, b=c=d==4500mm, e=4500mm, α=245.5°.

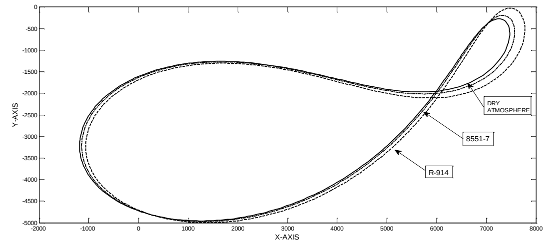

Figure 6 Coupler curve (figure eight crunodes) deviations for different material under hygrothermal environment, a=3000mm, b=c=4500mm, d=5000mm,e=4500mm, γ=270°

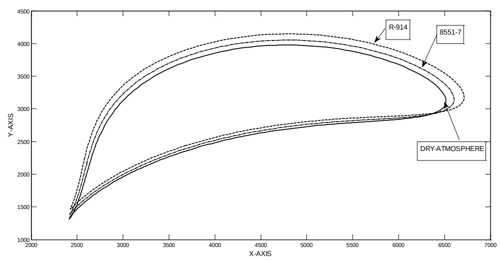

Figure 7 Coupler curve (teardrop cusp) deviation for different material under hygrothermal environment, a=2250mm, b=c=d=4500mm, e=5000mm, γ=336° .

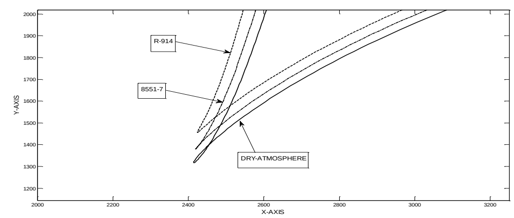

Figure 8 Coupler curve deviation under hygrothermal environment, a=2250mm, b=c=d==4500mm, e=5000mm,γ=336°, figure eight crunodes in dry atmosphere transforms to Cusp under hygrothermal environment**.**

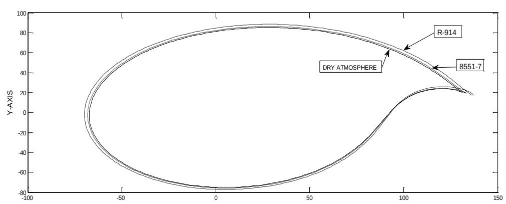

Figure 9 Coupler curve (teardrop cusp) deviation for different material under hygrothermal environment, a=100mm, b=c =130mm, d=120mm, e=33mm, γ=320°

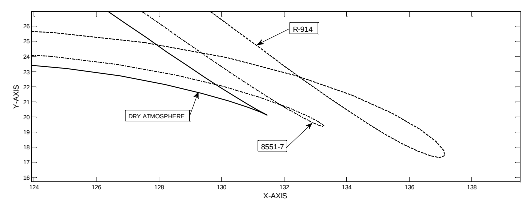

Figure 10 Coupler curve deviation for different material under hygrothermal environment , a teardrop Cusp in dry atmosphere transforms to figure eight crunodes under hygrothermal environment, a=100mm, b=c =130mm, d=120mm, e=33mm, γ=320°.

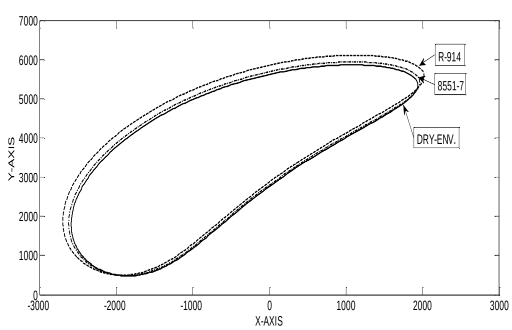

Figure 11 Coupler curve (kidney bean) deviation for different material under hygrothermal environment , a=2250mm, b=c =d=4500, e=3750mm, γ=45°

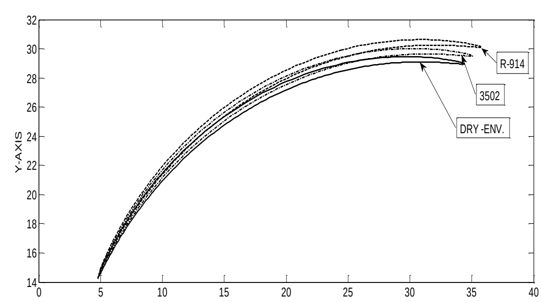

Figure 12 Coupler curve (crescent) deviation for different material under hygrothermal environment, a=15mm, b=c =d=e=30mm, γ=358°**.**

5. CONCLUSION

Results obtained indicate a clear deviation in kinematic performance of the four bar mechanism also deviation in shape of coupler curves is observed, for example Cusp in dry atmosphere transforms into figure eight crunodes under hygrothermal environment, figure eight crunodes in dry atmosphere transforms to Cusp under hygrothermal environment, a teardrop Cusp in dry atmosphere

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transforms to figure eight crunodes under hygrothermal environment. The above deviations establish the fact that motion characteristics of kinematic chain made up of resins, changes under hygrothermal environment. The above fact needs to be considered while designing the mechanism for specific objective made up of polymer materials while working in hygrothermal environment.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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