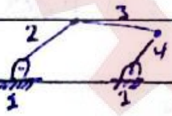
Machinary 335

- machine: A Device that transforms power and motion. It consists of mechanisms (linkages).

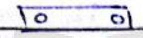
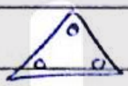
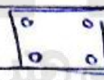
- mechanisms: A machine component that transmits motion. It consists of Two or more bodies (links) connected by joints (pairs).

← اذا ثبتت الأرض link تصبح link واحد إلا اذا سمحت بـ Relative motion

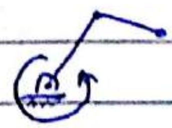
- link: A body that has at least two points (nodes) for for attachment to other links.



← Ground link هو الـ link الثابت في ال machine رمزه =

- Based on the number of links connected a link may be classified as
  - Binary link 
  - Ternary link (3 point)  ← شيء بشكل لأبعاد الروابط.
  - Quaterrary (4 point) 

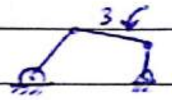
- Based on the type of motion links may be classified as:
  Ground of fixed (stationary)

  - Crank: 1 full Rotation
    2 pivoted to Grond
    } شروط Crank 

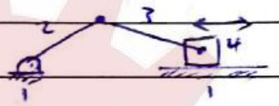
  - Rocker: 1 oscillation
    2 pivoted to Ground
    } 

No.

- Coupler or connecting rod:
  1. General plane motion
  2. Connected to other moving links.

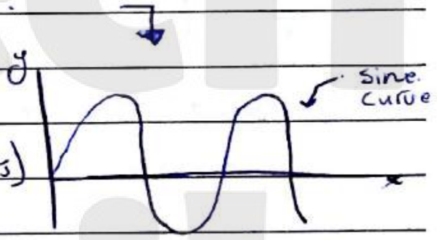


- slider: 1. sliding motion (translation)



** Degree of Freedom (DoF)

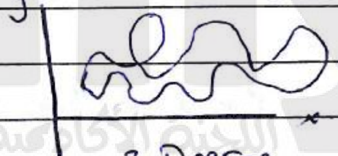
The number of independent coordinates (parameters) needs to describe the position of an object.



اذا مشينا على curve بنقدر نوجد علاقة بين y, x بيعتبر one Degree.

** Joints (Pairs, Kinematic Pairs, Pairing elements)

Elements by which two or more Links are joined together in such a way that motion is allowed.



3 Degree

بسبب وجود Rotation حول z.

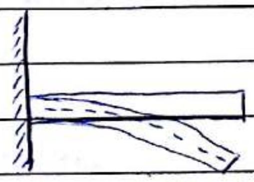
- Joint classification: (see fig 2.3)

[I] Based on the Type of contact

→ Lower pair: Joints with surface contact.

E.x Revolute Joint (R)

Prismatic (sliding) (P)

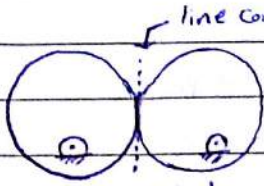


∞ Degree.

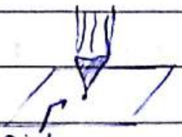
→ Higher Pair: Joints with point or line contact.

No.

Ex



Cam Joint



R : Translation
P : Rotation

$\boxed{II}$ Based on the number of (D.o.f) allowed by Joint :

→ 1 (Dof) joint : R, P Joint (Full Joint)

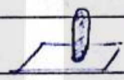
→ 2 (Dof) Joint : Roll slide Joint (Half Joint) Ex Cam.
(RP)

$\boxed{III}$ Based on the number of links Joint : [Joint oRder] :

1^{st} order Joint : 2 links Jointed.
2^{nd} order Joint : 3 links Joined.
K^{th} order Joint : (K+1) links Joined.

$\boxed{IV}$ Based on the type of physical clousure

Form closed — Force closed



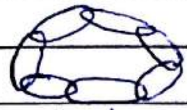
تحتاج الى قوة لتثبيتها على السطح

** Kiematic Chain : A system Consisting of a number of links Connected together by Joints.

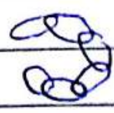
closed — open

كل link مربوط بل الأقل بـ Two link

واحد على الأقل link مربوط بـ one link



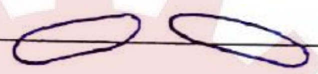
Closed



open.

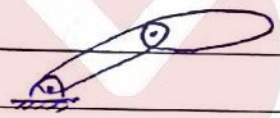
No.

** Mobility (D.o.F) of mechanism...

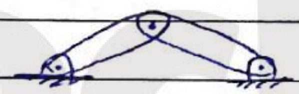


6. D.o.F

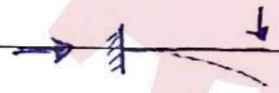
4 D.o.F



2 D.o.F

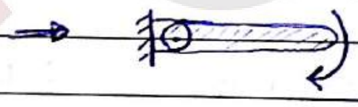


Zero D.o.F ← structure



structure

لأنه حدث فيه Deflection



mechanisem.

بسبب حدوث الدوران.

$$M = 3(L-1) - 2J_1 - J_2$$

↳

M : Mobility (D.o.F) of the mechanizem.

L : number of link.

J_1 : No. of Joints with 1 d.o.f.

J_2 : No. of Joints with 2 d.o.f.

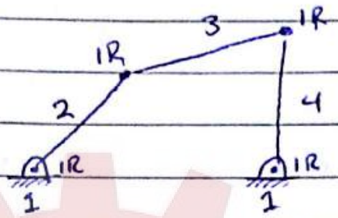
⇒ $M \geq 1$: mechanisem (linkage)

$M \leq 0$: structure $\begin{cases} = 0 & \text{stat. def.} \\ < 0 & \text{stat. Indef.} \end{cases}$

No.

$M = 1$ يعني
1 input → 1 output

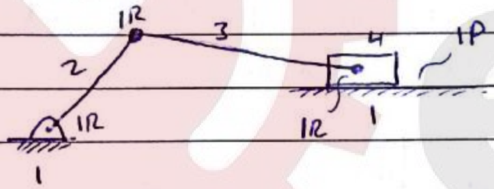
E.x 4-Bar



$L = 4$, $J_1 = 4$ (4R)
$J_2 = 0$

$$M = 3(4-1) - 2(4) - 0 = 1$$

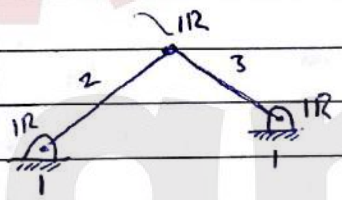
E.x Slider - Crank



$L = 4$, $J_1 = 4$ (3R+1P)
$J_2 = 0$

$M = 1$

E.x

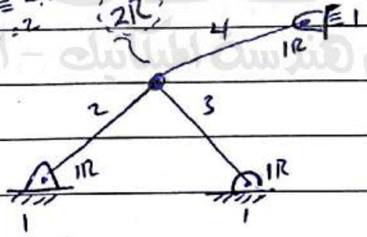


$L = 3$
$J_1 = 3$
$J_2 = 0$

$M = 3(3-1) - 2(3) - 0$
$= 0$ → structure.
→ staticly det.
→ Truss

Joint واحد
link 3 ربط
3-1=2

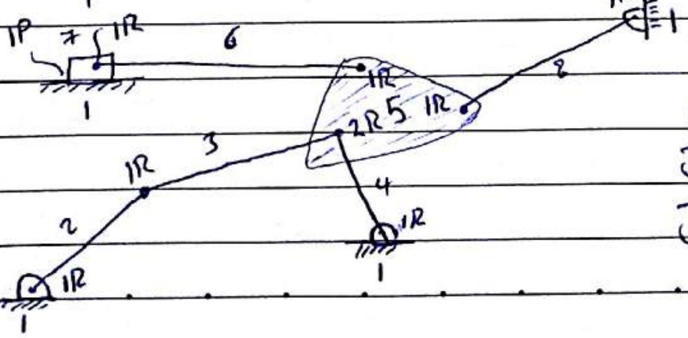
E.x



$L = 4$
$J_1 = 5$ (5R)
$J_2 = 0$

$M = -1$
stat. indet. structure.

E.x

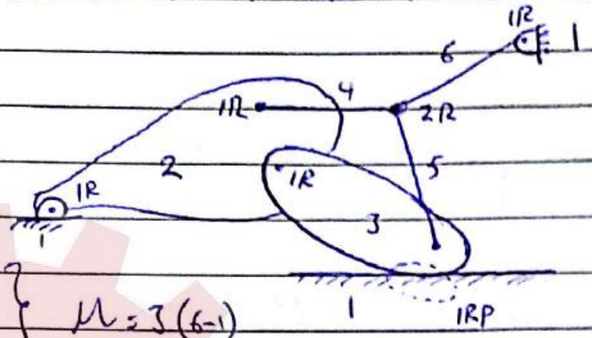


$L = 8$
$J_1 = 10$ (9R + 1P)
$J_2 = 0$

$M = 1$

No. ____________

E.x



اذا شغلنا spring خ اعتبارها 6 بعد link.

$L = 6$

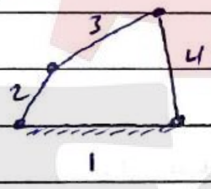
$J_1 = 7\ (7R)$

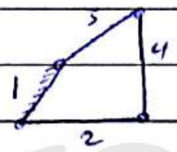
$J_2 = 1\ (1RP)$ — Cam Joint

$\mu = 3(6-1) - 2(7) - 1 = 0$

** Inversion of a mechanism :

Anew mechanism that Results when the fixed link is allowed to move and another link is fixed.





- 4-Bar

Grashof (1, 2, 3, 4) — Non-Grashof

Self Reading من الكتاب

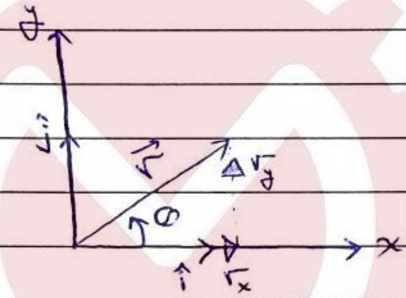
L_1, L_2, L_3, L_4

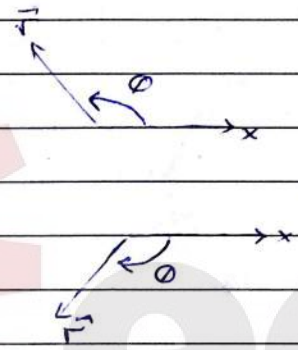
S (الأقصر), L (الأطول), P, Q (الطولين الباقيين) $\Rightarrow$ Grashof: $(S+L) \leq (P+Q)$

No.

** Position analysis of mechanism ...

Analytical Approach (Vector) — Numerical. — Graphical.



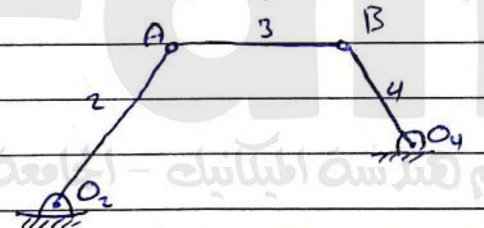


① ابدأ من +x axes.

$r_x = r\cos\theta \quad , \quad r_y = r\sin\theta$

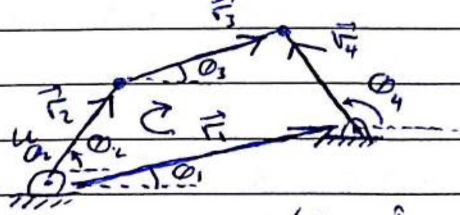
$$\vec r = r\cos\theta\,\hat i + r\sin\theta\,\hat j \rightarrow \vec r = r\underbrace{(\cos\theta\,\hat i + \sin\theta\,\hat j)}_{\hat u_\theta}$$

* Vector loop Equation [loop closure Equ.] :-



moving link بتربط link Two متحركات
Ground link بتربط link مع link Ground.

loop : $O_2 \rightarrow A \rightarrow B \rightarrow O_4 \rightarrow O_2$



$$\vec r_2 + \vec r_3 - \vec r_4 - \vec r_1 = \vec 0$$

$$r_2\vec u_{\theta_2} + r_3\vec u_{\theta_3} - r_4\vec u_{\theta_4} - r_1\vec u_{\theta_1} = \vec 0$$

$$r_2(\cos\theta_2\hat i + \sin\theta_2\hat j) + r_3(\cos\theta_3\hat i + \sin\theta_3\hat j) - r_4(\cos\theta_4\hat i + \sin\theta_4\hat j) - r_1(\cos\theta_1\hat i + \sin\theta_1\hat j) = \vec 0\,\hat i + 0\,\hat j$$

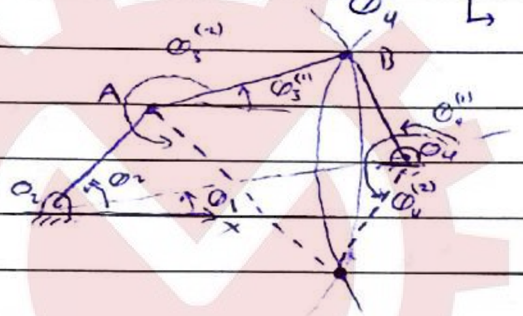
No.

x-Comp: $r_2 \cos\theta_2 + r_3 \cos\theta_3 - r_4 \cos\theta_4 - r_1 \cos\theta_1 = 0$

y-Comp: $r_2 \sin\theta_2 + r_3 \sin\theta_3 - r_4 \sin\theta_4 - r_1 \sin\theta_1 = 0$

4-Bar: Given: $\theta_1, r_1, r_2, r_3, r_4$ + Input: θ_2

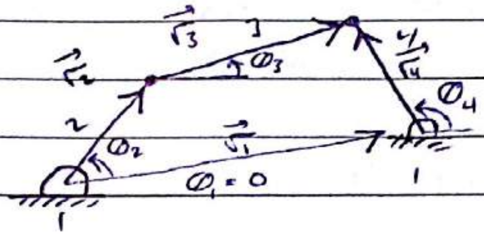
Find θ_3, θ_4 → Analytical, Numirical, Graph.



**

mid 4/11

No.



θ_3 , θ_4 مجاهيل وبدي اتخلص من θ_3 لأنه بدي θ_4

* L.C.E:

$$r_2 \hat{u}_{\theta_2} + r_3 \hat{u}_{\theta_3} - r_4 \hat{u}_{\theta_4} - r_1 \hat{u}_0 = 0$$

* $\rightarrow$ x-comp. : $r_2 \cos\theta_2 + r_3 \cos\overset{?}{\theta_3} - r_4 \cos\overset{?}{\theta_4} - r_1 = 0$

$\rightarrow$ y-comp. : $r_2 \sin\theta_2 + r_3 \sin\overset{?}{\theta_3} - r_4 \sin\overset{?}{\theta_4} = 0$

* $r_3 \hat{u}_{\theta_3} = r_1 \hat{u}_0 - r_2 \hat{u}_{\theta_2} + r_4 \hat{u}_{\theta_4}$ <u>dot</u> each side by itself.

$$\rightarrow r_3^2 = (r_1 \hat{u}_0 - r_2 \hat{u}_{\theta_2} + r_4 \hat{u}_{\theta_4}) \cdot (r_1 \hat{u}_0 - r_2 \hat{u}_{\theta_2} + r_4 \hat{u}_{\theta_4})$$

$$= r_1^2 + r_2^2 + r_4^2 - 2 r_1 r_2 \cos\theta_2 + 2 r_1 r_4 \cos\theta_4 - 2 r_2 r_4 (\cos(\theta_4 - \theta_2))$$

لأنه في عنا زاوية مجهولة بنفكها بهاي الطريقة. $[\cos\theta_4 \cdot \cos\theta_2 + \sin\theta_4 \cdot \sin\theta_2]$

$$\rightarrow A\cos\theta_4 + B\sin\theta_4 + C = 0$$

$A = 2 r_1 r_4 - 2 r_2 r_4 \cos\theta_2$

$B = -2 r_2 r_4 \sin\theta_2$

$C = r_1^2 + r_2^2 - r_3^2 + r_4^2 - 2 r_1 r_2 \cos\theta_2$

نستخدم لتقصير مشوار الحل $\rightarrow$ $\cos\theta_4 = \dfrac{1 - \tan^2\left(\frac{\theta_4}{2}\right)}{1 + \tan^2\left(\frac{\theta_4}{2}\right)}$, $\sin\theta_4 = \dfrac{2\tan\left(\frac{\theta_4}{2}\right)}{1 + \tan^2\left(\frac{\theta_4}{2}\right)}$

من باب الاختصار $\rightarrow$ let $x = \tan\left(\frac{\theta_4}{2}\right)$

No.

بتجميع الحدود و الضرب ب $(1+x^2)$ للمعادلة.

$$A\left(\frac{1-x^2}{1+x^2}\right)+\frac{2Bx}{1+x^2}+C=0$$

$$(C-A)x^2+(2B)x+(A+C)=0$$

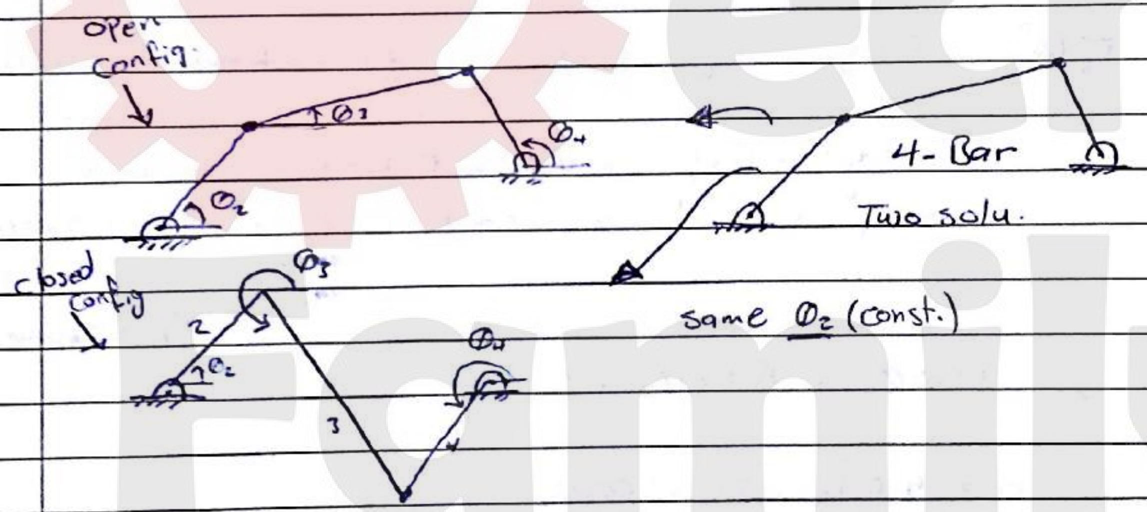
↳ same of

$$ax^2+bx+c=0 \rightarrow x_{1,2}=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

↑ Two solution.

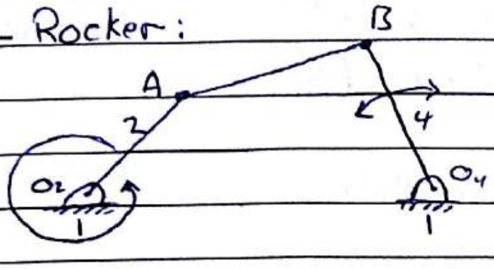
$$\tan\left[\frac{(\theta_4)_{1,2}}{2}\right]=\frac{-2B\pm\sqrt{(2B)^2-4(C-A)(C+A)}}{2(C-A)}$$

$$(\theta_4)_{1,2}=2\tan^{-1}x_{1,2}$$ → Then find $(\theta_3)_{1,2}$ from the component equ.



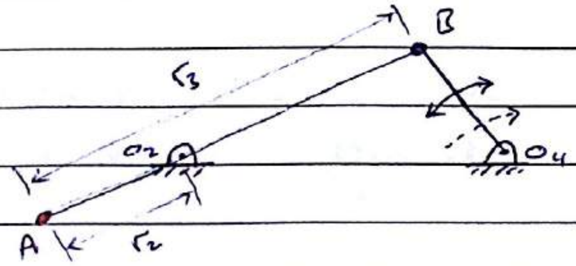
** Limiting position (toggle position):

- Crank - Rocker:

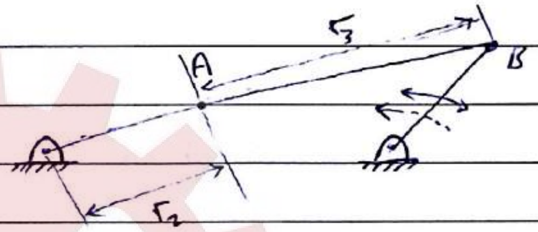


No.

Limit Pos. 1



Limit Pos. 2



\# H.W. #1 : Due Wed 8/10

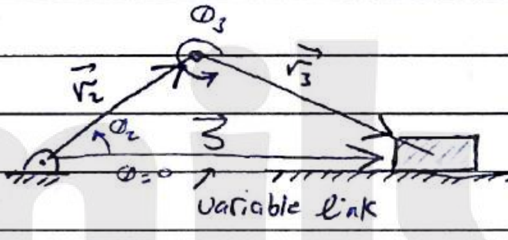
4-6(a) , find θ_2 in limit position.

4-7(a) , find θ_2 " " " .

Cover Page.

Course title
Sec. 2
H.W #1
Date
Name
Seat NO.
Id NO.

** Slider-Crank :-



Given: r_2 , r_3 , γ

input: θ_2

Find: θ_3 , S

$$\check{r}_2 \hat{u}_{\theta_2} + \check{r}_3 \hat{u}_{\theta_3} - S\hat{u}_{0} = 0$$

To eleminate θ_3 :

$$r_3 \hat{u}_{\theta_3} = S\hat{u}_0 - r_2 \hat{u}_{\theta_2}$$

dot each side by it self.

تطبيق Cosin Law.

$\Rightarrow$

$$r_3^2 = S^2 + r_2^2 - 2Sr_2 \cos\theta_2$$

$$AS^2 + BS + C = 0$$

$$S_{1,2} = \frac{-B \mp \sqrt{B^2 - 4AC}}{2A}$$

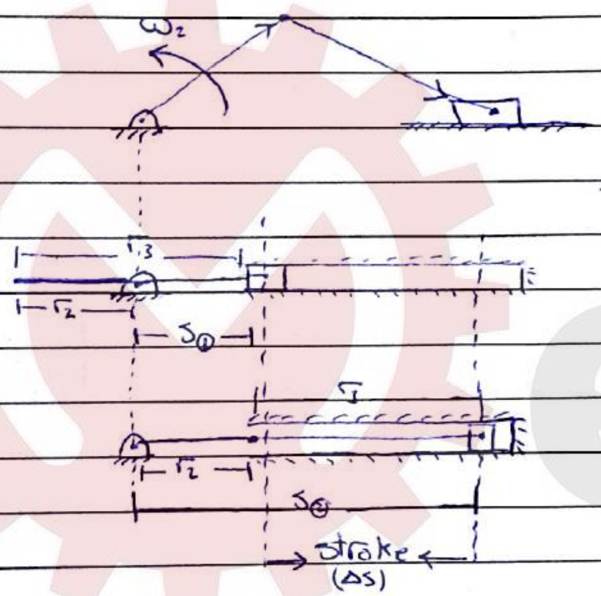
$$A = 1 \quad , \quad B = -2r_2\cos\theta_2 \quad , \quad C = r_2^2 - r_3^2$$

No.

OR x-Comp. : $r_2 \cos\theta_2 + r_3 \cos\theta_3 - S = 0$ — find S

y-Comp. : $r_2 \sin\theta_2 + r_3 \sin\theta_3 = 0 \rightarrow$ find θ_3

→ Limit postion:

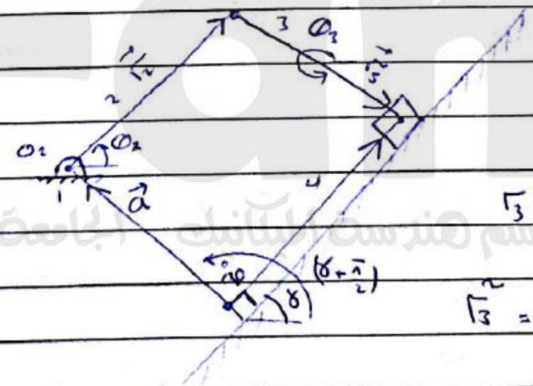


$S_{①} = r_3 - r_2$

$S_{②} = r_2 + r_3$

$\Delta S = S_{②} - S_{①} = 2r_2$

-x-*



L.C.E:

$$\check{r}_2 \hat{u}_{\theta_2} + \check{r}_3 \hat{u}_{\theta_3} - S\hat{u}_{\gamma} + \check{a}\hat{u}_{\gamma+\frac{\pi}{2}} = 0$$

$$r_3 \hat{u}_{\theta_3} = S\hat{u}_{\gamma} - a\hat{u}_{\gamma+\frac{\pi}{2}} - r_2 \hat{u}_{\theta_2} \quad \underline{\underline{\text{Dot}}}$$

$$r_3^2 = S^2 + a^2 + r_2^2 - \cancel{2aS\cos(\tfrac{\pi}{2})}$$
$$-2Sr_2\cos(\theta_2-\gamma) + 2ar_2\underbrace{\cos(\theta_2-\gamma-\tfrac{\pi}{2})}_{\sin(\theta_2-\gamma)}$$

$$AS^2 + BS + C = 0$$

$A = 1$

$B = -2r_2\cos(\theta_2-\gamma)$

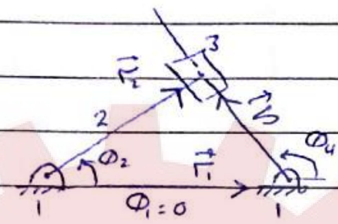
$C = a^2 + r_2^2 - r_3^2 + 2ar_2\sin(\theta_2-\gamma)$

$\rightarrow S_{1,2} = \checkmark$

go Back and find θ_3

No.

** Inverted slider-crank (sliding-contact mech.) :-



L.C.E :

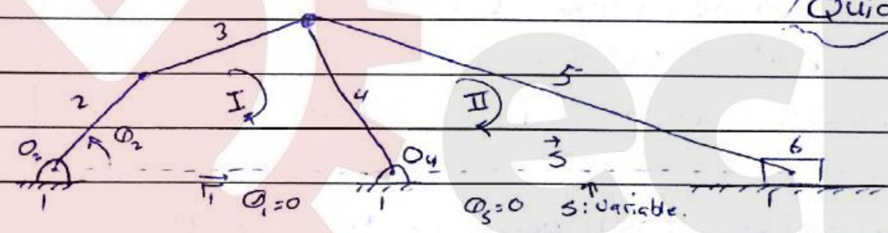
$$\vec{r}_2 \hat{U}_{\theta_2} - S \hat{U}_{\theta_4} - r_1 \hat{U}_0 = \vec{0}$$

$$S \hat{U}_{\theta_4} = r_2 \hat{U}_{\theta_2} - r_1 \hat{U}_0$$

$$S^2 = r_1^2 + r_2^2 - 2 r_1 r_2 \cos\theta_2$$

/Quick Return/

→



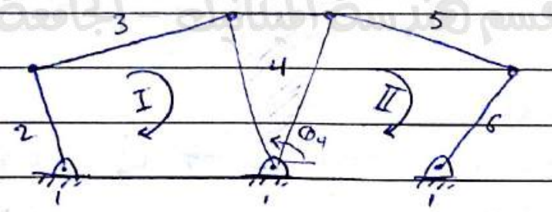
Given : $r_1, r_2, r_3, r_4, r_5, \theta_1, \theta_5$

input : θ_2

find : S

معادلتين !!
لانه فيه
$(\theta_3, \theta_4, \theta_5, S)$ Two loop. لأن

→ Watt's six-bar mechanism :



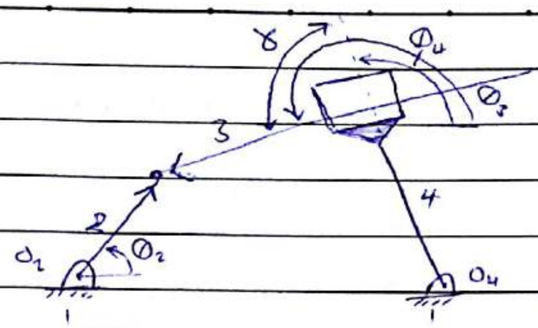
Give : θ_2

find : θ_6

??

*

No.



$\check{\vec{r}}_2, \check{\vec{r}}_1, \check{\theta}, \check{\vec{r}}_4$

Give: ω_2 معادلة

find: S, θ_3, θ_4 مجهول واحد

$\Downarrow$

$\theta_3 = \theta_4 + \gamma$

** Project → Due Mon. 27/11/2014

- Choose a mechanism (≥ 5 bar's)
- Explain and Application.
- Kinematic Analysis (Pos., Velocity, acc.).
- Dynamic Analysis
- Animation. [software, working model 2D].

** Velocity Analysis :-

$$\vec{V} = \frac{\partial \vec{r}}{\partial t} \quad , \quad \frac{\partial \hat{i}}{\partial t} = 0 = \frac{\partial \hat{j}}{\partial t} = \frac{\partial \hat{k}}{\partial t}$$

$$\frac{d\hat{u}_\theta}{dt} = \frac{d}{dt}\overbrace{(\cos\theta\,\hat{i} + \sin\theta\,\hat{j})}^{\hat{u}_\theta}$$

Note

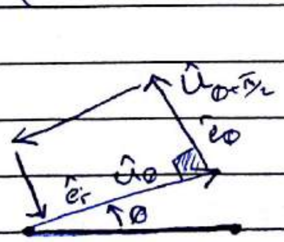
$$\frac{\partial (\ )}{\partial t} = \frac{\partial (\ )}{\partial \theta}\,\frac{\partial \theta}{\partial t} \quad , \quad \frac{\partial \theta}{\partial t} = \dot{\theta} = \omega$$

$$\frac{d\hat{u}_\theta}{dt} = -(\sin\theta)\dot{\theta}\,\hat{i} + (\cos\theta)\dot{\theta}\,\hat{j}$$

$$\dot{\hat{u}}_\theta = \dot{\theta}\,\overbrace{(-\sin\theta\,\hat{i} + \cos\theta\,\hat{j})}^{\hat{u}_{\theta+\frac{\pi}{2}}}$$

$\hat{u}_{\theta+\frac{\pi}{2}}$?كيف → $\hat{u}_{\theta+\frac{\pi}{2}} = \cos(\theta+\frac{\pi}{2})\hat{i} + \sin(\theta+\frac{\pi}{2})\hat{j}$

$= -\sin\theta + \cos\theta$

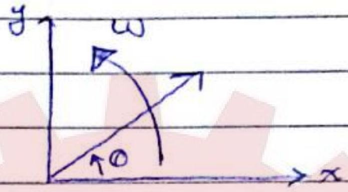


No.

الاول × مشتقة الثاني + (مشتقة الاول) × الثاني

$$\vec{r} = r\,\hat{u}_\theta \rightarrow \frac{d\vec{r}}{dt} = \frac{dr}{dt}\hat{u}_\theta + r\frac{d\hat{u}_\theta}{dt}$$

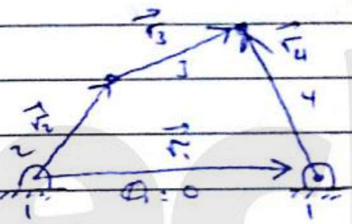
$$= \dot{r}\,\hat{u}_\theta + r\,\dot{\hat{u}}_\theta \qquad r\dot{\theta}\,\hat{u}_{\theta+\frac{\pi}{2}}$$



(ω) is a vector

$$\vec{\omega} = \overset{ccw}{\underset{cw}{\pm}}\ \dot{\theta}\ \hat{k}$$

* 4 - Bar :-



لا نبدأ في velocity إلا بعد ما نحل position والمعادلات وتحليلات

Given: $r_1, r_2, r_3, r_4, \theta_1$

input: θ_2, ω_2

↓

solve: θ_3, θ_4

Find $\vec{\omega}_3, \vec{\omega}_4$ ← المطلوب

دائما نبدأ في ايجاد الحل لو اعطانا position

L.C.E : $r_2\hat{u}_{\theta_2} + r_3\hat{u}_{\theta_3} - r_4\hat{u}_{\theta_4} - r_1\hat{u}_{\theta_1} = 0$

V.E : $\frac{d}{dt}(\text{L.C.E})$

$$\rightarrow \left(\cancel{\dot{r}_2\hat{u}_{\theta_2}} + r_2\omega_2\hat{u}_{\theta_2+\frac{\pi}{2}}\right) + \left(\cancel{\dot{r}_3\hat{u}_{\theta_3}} + r_3\omega_3\hat{u}_{\theta_3+\frac{\pi}{2}}\right)$$

$$-\left(\cancel{\dot{r}_4\hat{u}_{\theta_4}} + r_4\omega_4\hat{u}_{\theta_4+\frac{\pi}{2}}\right) - \left(\cancel{\dot{r}_1\hat{u}_{\theta_1}} + \cancel{r_1\omega_1}\hat{u}_{\theta_1+\frac{\pi}{2}}\right) = 0$$

$$\rightarrow r_2\omega_2\hat{u}_{\theta_2+\frac{\pi}{2}} + r_3\omega_3\hat{u}_{\theta_3+\frac{\pi}{2}} - r_4\omega_4\hat{u}_{\theta_4+\frac{\pi}{2}} = 0$$

Sol 1 |: x-Vel: $-r_2\omega_2\sin\theta_2 - r_3\omega_3\sin\theta_3 + r_4\omega_4\sin\theta_4 = 0$ ---(1)

y-Vel: $r_2\omega_2\cos\theta_2 + r_3\omega_3\cos\theta_3 - r_4\omega_4\cos\theta_4 = 0$ ---(2)

⇒ Find ω_3, ω_4

Sol 2 |: To elemenate ω_3:

ضربها dot $\cdot\ \hat{u}_{\theta_3}$

$$r_2\omega_2\overset{\sin(\theta_3-\theta_2)}{\hat{u}_{\theta_2+\frac{\pi}{2}}} + \cancel{r_3\omega_3\overset{0}{\hat{u}_{\theta_3+\frac{\pi}{2}}}} - r_4\omega_4\overset{\sin(\theta_3-\theta_4)}{\hat{u}_{\theta_4+\frac{\pi}{2}}} = 0$$

$$r_2\omega_2\sin(\theta_3-\theta_2) - r_4\omega_4\sin(\theta_3-\theta_4) = 0$$

$$\Rightarrow \omega_4 = \left[\frac{r_2\sin(\theta_3-\theta_2)}{r_4\sin(\theta_3-\theta_4)}\right]\omega_2$$

→ then Find ω_3 ✓

$$\hat{u}_{\theta_2+\frac{\pi}{2}} \cdot \hat{u}_{\theta_3}$$

$$(-\sin\theta_2\hat{i} + \cos\theta_2\hat{j})\cdot(\cos\theta_3\hat{i} + \sin\theta_3\hat{j})$$

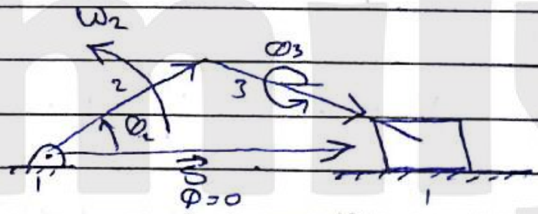
$$= -\sin\theta_2\cos\theta_3 + \sin\theta_3\cos\theta_2$$

$$= \sin\theta_3\cos\theta_2 - \cos\theta_3\sin\theta_2$$

$$= \sin(\theta_3-\theta_2)$$

* slider-crank:-

Find $\dot{S}$, ω_3



L.C.E :-

$$r_2\hat{u}_{\theta_2} + r_3\hat{u}_{\theta_3} - S\hat{u}_0 = 0$$

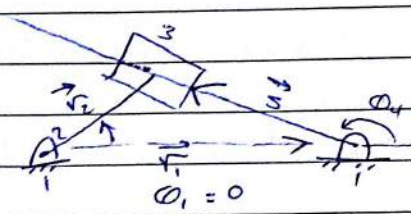
V.E :- $r_2\omega_2\hat{u}_{\theta_2+\frac{\pi}{2}} + r_3\omega_3\hat{u}_{\theta_3+\frac{\pi}{2}} - \dot{S}\hat{u}_0 = 0$ ($\cdot\ \hat{u}_{\theta_3}$ to find $\dot{S}$)

$$\rightarrow \dot{S} = \frac{r_2\omega_2\sin(\theta_3-\theta_2)}{\cos\theta_3}$$

No.

L.C.E :

$$r_2 \hat{u}_{\theta_2} - s\hat{u}_{\theta_4} - r_1 \hat{u}_0 = 0$$



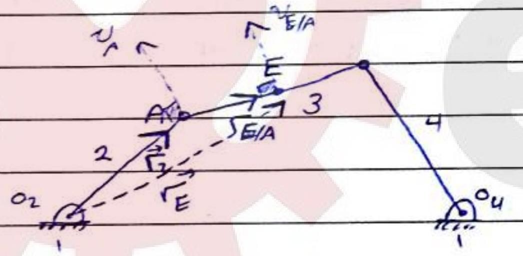
V. E :

$$r_2 \omega_2 \hat{u}_{\theta_2 + \frac{\pi}{2}} - \dot{s}\hat{u}_{\theta_4} - s\omega_4 \hat{u}_{\theta_4 + \frac{\pi}{2}} = 0 \qquad (\cdot\, \hat{u}_{\theta_4})$$

$$r_2 \omega_2 \sin(\theta_4 - \theta_2) = \dot{s}$$

Self Reading :-
→ Angular Velocity Ratio (m_V)
→ Torque Ratio (m_T)
→ Mechanical Advantage (m_A)

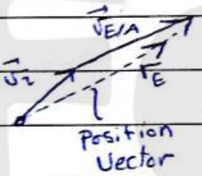
**



Find $\vec{v}_E$?

$$\vec{v}_E = \vec{v}_A + \vec{v}_{E/A}$$

$$|\vec{v}_A| = \omega_2 r_2 \quad , \quad |\vec{v}_{E/A}| = \omega_3 (\overline{AE})$$



$$\vec{r}_E = \underset{(A)}{\vec{r}_2} + \vec{r}_{E/A} = r_2 \hat{u}_{\theta_2} + (\overline{AE})\hat{u}_{\theta_3}$$

$$\vec{V}_E = \frac{d\vec{r}_2}{dt} + \frac{d\vec{r}_{E/A}}{dt}$$

$$= r_2\omega_2 \hat{u}_{\theta_2 + \frac{\pi}{2}} + (\overline{AE})\omega_3 \hat{u}_{\theta_3 + \pi/2}$$

** Instantaneous Center of Rotation:-

→ A point common مشترك to two links and has the same instant velocity in each link.

→ Some (I.C's) can be found by inspection (e.x pinjoint's.

No.

other Can be found by Kennedy's Rule).

→ No. of instant No I.C's :-

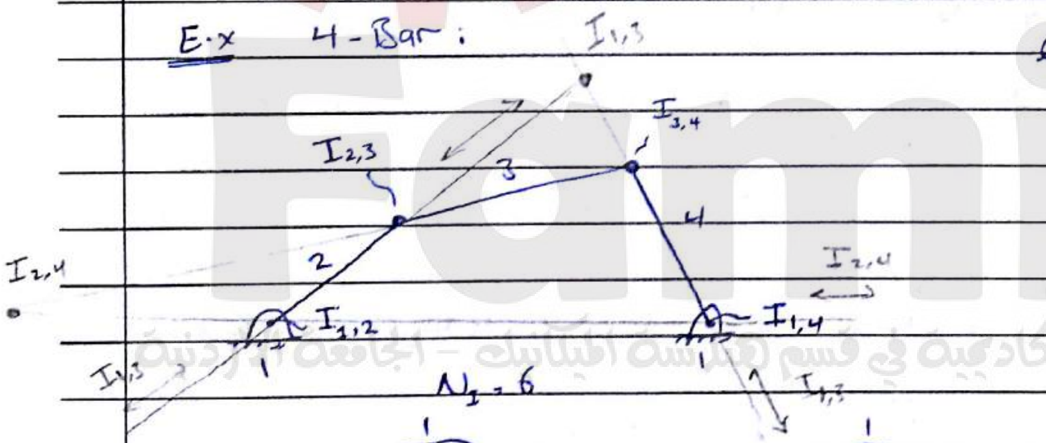
$$N_I = \frac{L(L-1)}{2} \quad ; \quad L: \text{No. of link's}$$

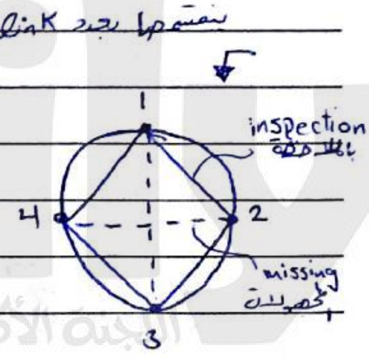
Ex 4-Bar : $N_I = \frac{4(4-1)}{2} = 6$

→ Kennedy's Rule :-

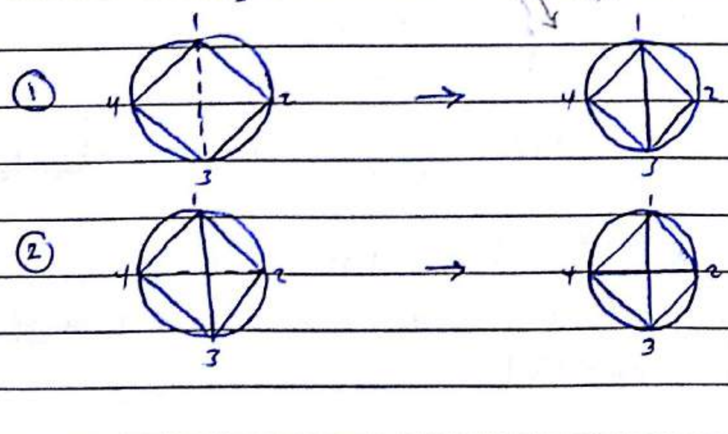
Any three bodies (→ link) in plane motion will have exactly three instant centers, and they will lie on the same straight line.

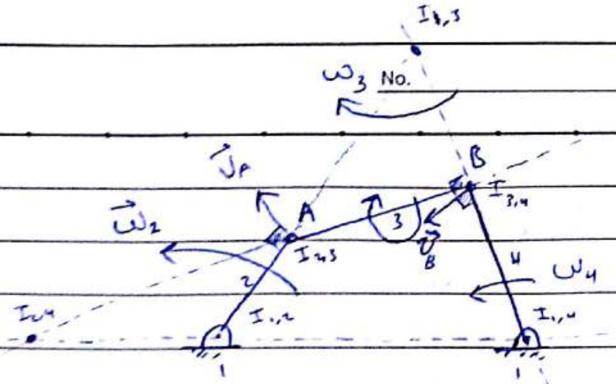
E.x 4-Bar :





$N_I = 6$





Given: Pos. + input $\vec{\omega}_2$

find $\vec{\omega}_3$, $\vec{\omega}_4$

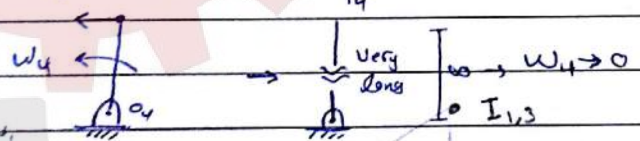
1) $v_A = \omega_2 r_2$, dir: ⊥ link$_2$

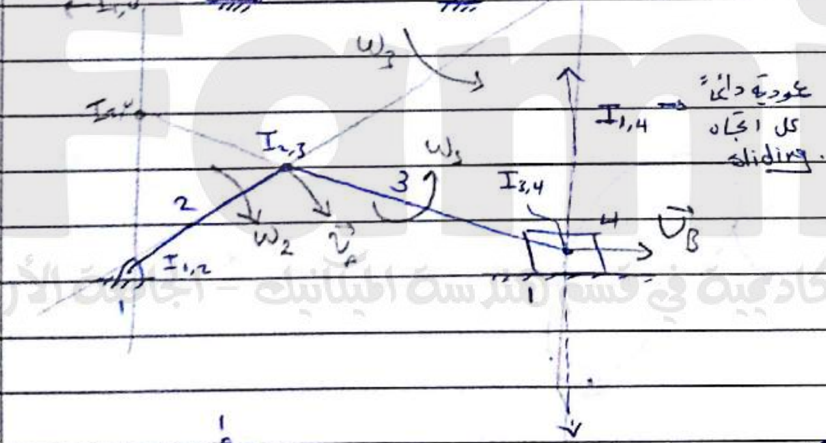
2) $v_A = \omega_3 (\overline{AI_{1,3}}) \rightarrow \omega_3 = \frac{v_A}{\overline{AI_{1,3}}}$; dir: CW

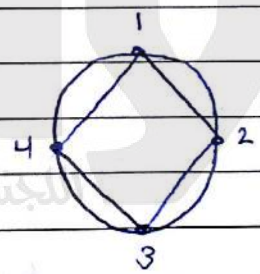
3) $v_B = \omega_3 (I_{1,3}B)$, dir ⊥ link 4

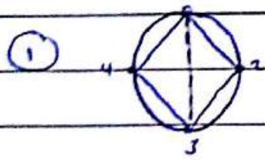
4) $v_B = \omega_4 r_4 \rightarrow \omega_4 = \frac{v_B}{r_4}$; dir: CCW

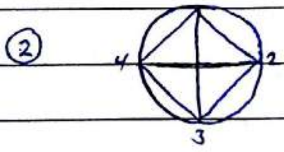
** $v_B = r_4 \omega_4 \rightarrow \omega_4 = \frac{v_B}{r_4}$











Given: Pos + ω_2 , find ω_3, $s = v_B = v_4$

No.

1) $V_A = \omega_2 r_2$, dir $\perp$ link 2

2) $\omega_3 = \dfrac{V_A}{\overline{AI_{1,3}}}$, dir : CCW

3) $V_B = \omega_3 \, (\overline{BI_{1,3}})$

→ H.W #2 Due Mon 27/10 ; 6-18 (b.c) , 7-15 (b)

suggested 6-13, 21 (b) , 44 , 61

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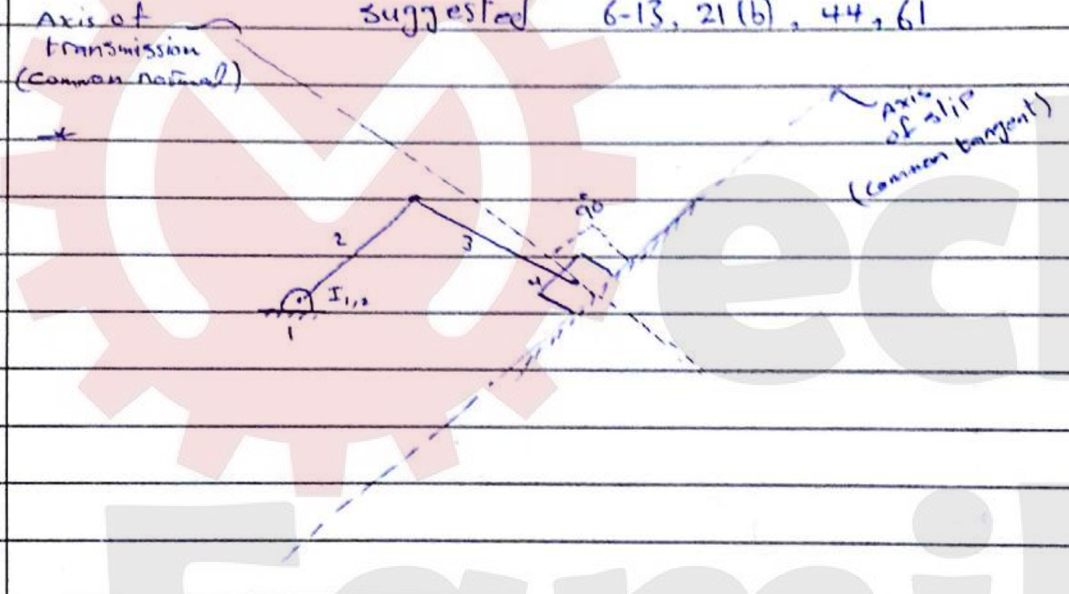

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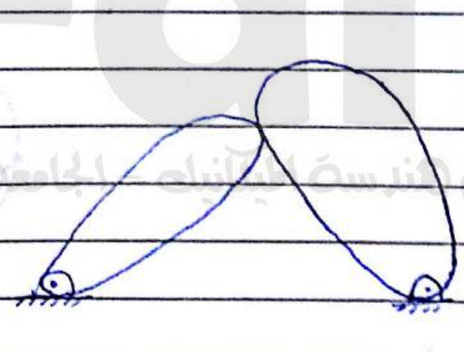
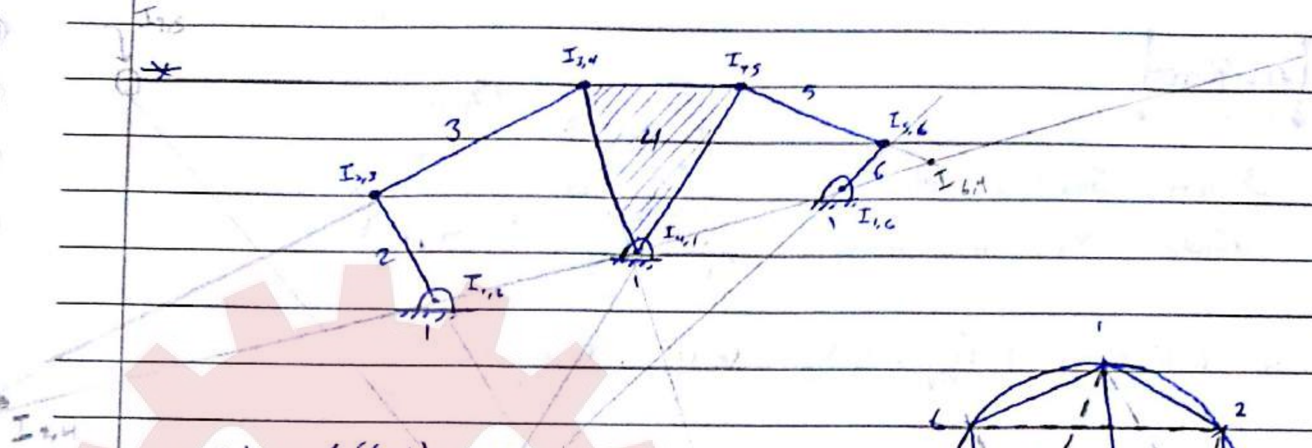
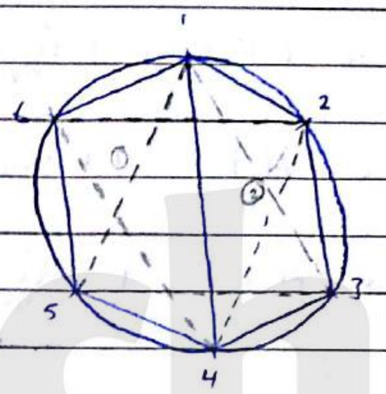


No.



$N_I = \frac{6(6-1)}{2} = 15$



** Acceleration Analysis :-

$\rightarrow \vec{r} = r\hat{u}_\theta$

$\rightarrow \vec{V} = \frac{d\vec{r}}{dt} = \dot{r}\hat{u}_\theta + r\dot{\theta}\hat{u}_{\theta+\frac{\pi}{2}}$

α: angular acc. = rad/s²

$\rightarrow \vec{a} = \frac{d\vec{V}}{dt} = \left(\ddot{r}\hat{u}_\theta + \dot{r}\dot{\hat{u}}_\theta\right) + \dot{r}\dot{\theta}\hat{u}_{\theta+\frac{\pi}{2}} + r\ddot{\theta}\hat{u}_{\theta+\frac{\pi}{2}} + r\dot{\theta}\dot{\hat{u}}_{\theta+\frac{\pi}{2}}$

$\dot{\theta}\hat{u}_{\theta+\frac{\pi}{2}}$ same (+)

Radial acc. Trans. acc.

$\Rightarrow \vec{a} = \left(\underbrace{\ddot{r}}_{a_{slip}} - \underbrace{r\omega^2}_{a_{normal}}\right)\hat{u}_\theta + \left(\underbrace{r\alpha}_{a_{tang}} + \underbrace{2\dot{r}\omega}_{a_{coriolis}}\right)\hat{u}_{\theta+\frac{\pi}{2}}$

Note

$\hat{u}_\theta = \cos\theta\,\hat{i} + \sin\theta\,\hat{j}$

$\hat{u}_{\theta+\frac{\pi}{2}} = -\sin\theta\,\hat{i} + \cos\theta\,\hat{j}$

$\dot{\hat{u}}_{\theta+\frac{\pi}{2}} = -\dot{\theta}\cos\theta\,\hat{i} - \dot{\theta}\sin\theta\,\hat{j}$

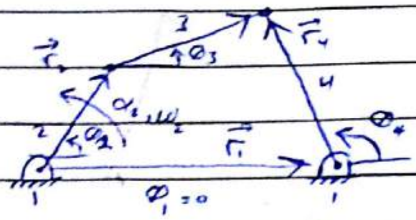
$= -\dot{\theta}\,\hat{u}_\theta$

No.

4-Bar

Given: Position, velocity

Find: α_3, α_4 input α_2



→ L.C.E: $r_2 \hat{u}_{\theta_2} + r_3 \hat{u}_{\theta_3} - r_4 \hat{u}_{\theta_4} - r_1 \hat{u}_{\theta_1} = 0$

→ V.E: $r_2 \omega_2 \hat{u}_{\theta_2+\frac{\pi}{2}} + r_3 \omega_3 \hat{u}_{\theta_3+\frac{\pi}{2}} - r_4 \omega_4 \hat{u}_{\theta_4+\frac{\pi}{2}} = 0$

→ A.E: $r_2 \alpha_2 \hat{u}_{\theta_2+\frac{\pi}{2}} - r_2 \omega_2^2 \hat{u}_{\theta_2} + r_3 \alpha_3 \hat{u}_{\theta_3+\frac{\pi}{2}} - r_3 \omega_3^2 \hat{u}_{\theta_3} - r_4 \alpha_4 \hat{u}_{\theta_4+\frac{\pi}{2}}$
$+ r_4 \omega_4^2 \hat{u}_{\theta_4} = 0$

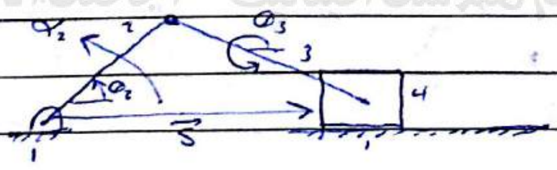
✓ sol.1 → x comp. → y comp.

✓ sol.2 To eliminate α_3 :- we dot $\cdot \hat{u}_{\theta_3}$

$r_2 \alpha_2 \sin(\theta_3 - \theta_2) - r_2 \omega_2^2 \cos(\theta_3 - \theta_2) - r_3 \omega_3^2 - r_4 \alpha_4 \sin(\theta_3 - \theta_4)$
$+ r_4 \omega_4^2 \cos(\theta_3 - \theta_4) = 0$ then find α_3.

slider_crank

CCW
$\vec{\alpha} = \pm \alpha \hat{k}$
CW
α, ω نفس الاتجاه
acc. يعني
اما اذا عكس بعض
Dec. يعني



Given: Pos. + Vel. + input α_2

Find: α_3 , $\ddot{S}$ (a_4)

→ L.C.E: $r_2 \hat{u}_{\theta_2} + r_3 \hat{u}_{\theta_3} - S \hat{u}_{\theta_0} = \vec{0}$

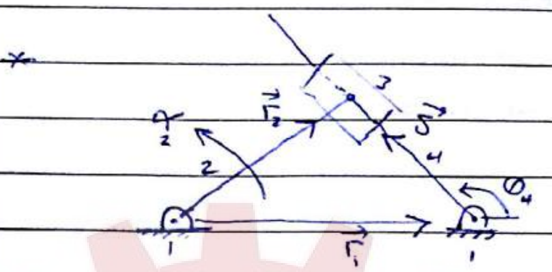
→ V.E: $r_2 \omega_2 \hat{u}_{\theta+\pi/2} + r_3 \omega_3 \hat{u}_{\theta_3+\pi/2} - \dot{S} \hat{u}_0 = 0$

→ A.E: $r_2 \alpha_2 \hat{u}_{\theta_2+\pi/2} - r_2 \omega_2^2 \hat{u}_{\theta_2} + r_3 \alpha_3 \hat{u}_{\theta_3+\pi/2} - r_3 \omega_3^2 \hat{u}_{\theta_3} - \ddot{S} \hat{u}_0 = 0$

No.

dot $(\cdot \hat{u}_{\theta_3}) \rightarrow \ddot{s} = \checkmark$

*



Given: Pos - vel. - input α_2

find: $\ddot{s}$, α_4

$\rightarrow$ L.C.E: $r_2 \hat{u}_{\theta_2} - s\hat{u}_{\theta_4} - r_1 \hat{u}_{0} = 0$

$\rightarrow$ V.E: $r_2 \omega_2 \hat{u}_{\theta_2+\frac{\pi}{2}} - \dot{s}\hat{u}_{\theta_4} - s\omega_4 \hat{u}_{\theta_4+\frac{\pi}{2}} = 0$

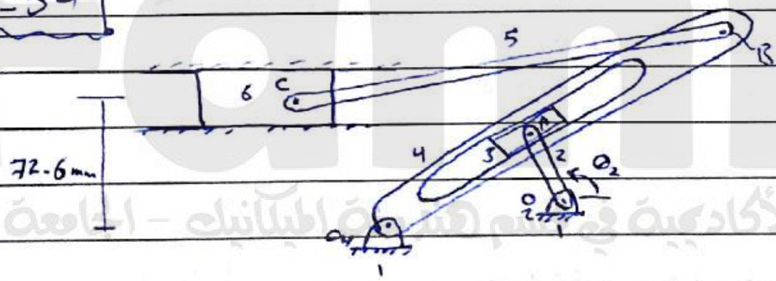
$\rightarrow$ A.E: $\Big[r_2\alpha_2 \hat{u}_{\theta_2+\frac{\pi}{2}} - r_2\omega_2^2 \hat{u}_{\theta_2} - \ddot{s}\hat{u}_{\theta_4} - \dot{s}\omega_4 \hat{u}_{\theta_4+\frac{\pi}{2}} - \dot{s}\omega_4 \hat{u}_{\theta_4+\frac{\pi}{2}}$

$- s\alpha_4 \hat{u}_{\theta_4+\frac{\pi}{2}} + s\omega_4^2 \hat{u}_{\theta_4} = \vec{0} \Big] \cdot \hat{u}_{\theta_4}$

$\hookrightarrow \ddot{s} = r_2\alpha_2 \sin(\theta_4 - \theta_2) - r_2\omega_2^2 \cos(\theta_4 - \theta_2) + s\omega_4^2$

then $\alpha_4 = \checkmark$

*7-54



$L_2 = 25.4$ mm

$L_4 = 120.9$ mm

$L_5 = 115.9$ mm

$O_4 , O_2 = 42.9$ mm @ $15.5°$

For $\theta_2 = 99°$

$\omega_2 = 10$ rad/s (CCW) = Const.

نستنتج $\alpha_2 = 0$ ← بما انه Const.

Find:

$\vec{a}_A$, $\vec{a}_B$, $\vec{a}_C$

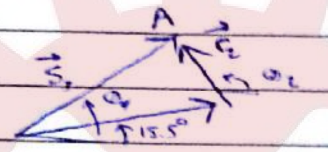
No.

Sol. :- Loop I : $O_4 \to O_2 \to A \to O_4$

Loop II : $O_4 \to B \to C \to D \to O_4$

or $O_2 \to A \to B \to C \to D \to O_4 \to O_2$

→ Loop I :



L.C.E. I :

$S_3 \hat{u}_{\theta_4} - 25.4 \hat{u}_{\theta_2} - 42.9 \hat{u}_{15.5°} = 0$

Rewrite ⇒ $S_3 \hat{u}_{\theta_4} = 25.4 \hat{u}_{\theta_2} + 42.9 \hat{u}_{15.5}$ [dot each self side by it self] for $\theta_2 = 99°$

$S_3^2 = 25.4^2 + 42.9^2 + 2(25.4)(42.9)\cos(99-15.5)$

⇒ $S_3 = 52.27$ mm

$$\theta_4 = \tan^{-1}\left[\frac{25.4\sin 99 + 42.9\sin 15.5}{25.4\cos 99 + 42.9\cos 15.5}\right] \quad \frac{y\text{-Comp.}}{x\text{-Comp.}}$$

V.E. I :

$\dot{S}_3 \hat{u}_{\theta_4} + S_3 \omega_4 \hat{u}_{\theta_4+\frac{\pi}{2}} - 25.4\,\omega_2 \hat{u}_{\theta_2+\frac{\pi}{2}} = 0$ $\Big\rfloor$ dot $\hat{u}_{\theta_4}$

$\dot{S}_3 = 25.4(+10)\sin(44.87-99)$

$\dot{S}_3 = -207.12$ (mm/s) Unit

$\cdot\, \hat{u}_{\theta_4+\frac{\pi}{2}}$: $\omega_4 = \dfrac{25.4(+10)\cos(44.87-99)}{52.27} = 2.81$ (rad/s) CCW

No.

$$\cancel{\ddot{S}_3 = S_3\omega_4^2 - 25.4\,\omega_2^2\cos(\theta_4-\theta_2) \rightarrow \ddot{S}_3 = -1057.56}$$

$\boxed{A.E.I :-}$

$$\ddot{S}_3\,\hat{u}_{\theta_4} + 2\dot{S}_3\,\omega_4\,\hat{u}_{\theta_4+\frac{\pi}{2}} + S_3\,\alpha_4\,\hat{u}_{\theta_4+\frac{\pi}{2}} - S_3\,\omega_4^2\,\hat{u}_{\theta_4} - 25.4\,\alpha_2\,\hat{u}_{\theta_2+\frac{\pi}{2}}$$

$$+\,25.4\,\omega_2^2\,\hat{u}_{\theta_2} = \vec{0}$$

$(\cdot\,\hat{u}_{\theta_4}) \rightarrow \ddot{S}_3 =$

$\rightarrow$ يمكن حساب $\vec{a}_A$ عن طريق اعتبار النقطة A نقطة على الـ Rod2

$$\vec{r}_A = \vec{r}_2 = 25.4\,\hat{u}_{\theta_2}$$

$$\vec{v}_A = \frac{d\vec{r}_A}{dt} = 25.4\,\omega_2\,\hat{u}_{\theta_2+\pi/2}$$

$$\vec{a}_A = \frac{d\vec{V}_A}{dt} = \cancel{25.4\,\alpha_2}^{\,0}\,\hat{u}_{\theta_2+\pi/2} - 25.4\,\omega_2^2\,\hat{u}_{\theta_2}$$

$$\vec{a}_A = -25.4\,(10)^2\,\hat{u}_{99^\circ} = 2540\,\hat{u}_{99^\circ} \rightarrow |\vec{a}_A| = 2540\ mm/s^2$$

$\rightarrow$ يمكن حساب $\vec{a}_B$ عن طريق اعتبار النقطة B نقطة على الـ Rod 4

$$\vec{r}_B = 120.9\,\hat{u}_{\theta_4} \rightarrow \vec{v}_B = 120.9\,\omega_4\,\hat{u}_{\theta_4+\pi/2}$$

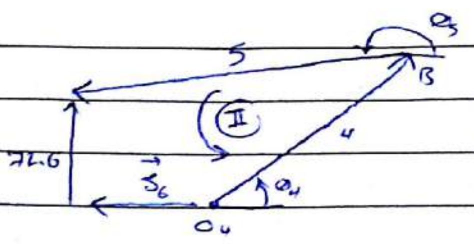
$$\vec{a}_B = 120.9\,\alpha_4\,\hat{u}_{\theta_4+\pi/2} - 120.9\,\omega_4^2\,\hat{u}_{\theta_4}$$

$$= (120.9)(-17.36)\,\hat{u}_{\theta_4+\pi/2} - 120.9\,(2.81)^2\,\hat{u}_{\theta_4}$$

$$= -2098.82\,\hat{u}_{\theta_4+\pi/2} - 954.64\,\hat{u}_{\theta_4}$$

No.

L.C.E II:



$$120.9\,\hat{u}_{\theta_4} + 115.9\,\overset{?}{\hat{u}}_{\theta_5} - 72.6\,\hat{u}_{90^\circ}$$

$$-\overset{?}{S_6}\,\hat{u}_{180^\circ} = \vec{0}$$

$$\rightarrow \text{y-comp:}\quad \theta_5 = \sin^{-1}\boxed{\frac{72.6 - 120.9\sin 44.37}{115.9}}$$

لأن $\vec{S}_6$ Horizontal نستخدم x.y comp. أسهل

$$\theta_5 = 185.91^\circ$$

هون اذا كانت حاسبة راح يطلع احتمالين بتوخذ المنطقي منهم

$$S_6 = 28.86\ mm$$

V.E. II:-

$$120.9\,\omega_4\,\hat{u}_{\theta_4+\frac{\pi}{2}} + 115.9\,\omega_5\,\hat{u}_{\theta_5+\pi/2} - \dot{S}_6\,\hat{u}_{180} = 0$$

$$\rightarrow \text{y-Comp:}\quad \omega_5 = 2.107\ rad/s$$

ما بنحتاج $\dot{S}_6$

بس اذا بدنا

اتجاه $\ddot{S}_6$ بنوخذ

منها acc. ,

dec. أو

A.E. II:-

$$\cancel{120.9\,\omega_4\,\hat{u}_{\theta_4+\frac{\pi}{2}} + 115.9\,\omega_5\,\hat{u}_{\theta_5+\pi/2} - \dot{S}_6\,\hat{u}_{180}}$$

$$\cdot\,\hat{u}_{\theta_5}$$

$$120.9\,\alpha_4\,\hat{u}_{\theta_4+\frac{\pi}{2}} - 120.4\,\omega_4^2\,\hat{u}_{\theta_4} + 115.9\,\overset{?}{\alpha_5}\,\hat{u}_{\theta_5+\frac{\pi}{2}} - 115.9\,\omega_5^2\,\hat{u}_{\theta_5} = \ddot{S}_6\,\hat{u}_{180}$$

$$\ddot{S}_6 = -107.78\ mm/s^2 = a_c = -1077.78\,\hat{u}_{180}$$

$$= 1077.78\,\hat{i}$$

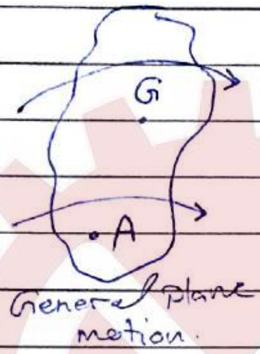
No.

suggested: 7 + 16, 20, 48, 50, 52

(Kinatic)

** Dynamic Analysis: Ch 11

_ Knowns: Kinematic + masses.



Equation of motion:

$$\sum \vec{F} = m\vec{a}$$

$$\sum \vec{M}_G = \sum (M_G)_{eff} = I_G \vec{\alpha}$$

$$\sum \vec{M}_A = \sum (\vec{M}_A)_{eff}$$

Note:
Centroid → geometric center
center of mass
center of gravity
نفس الشي لكن ظرفي
homogenous بتكون بحسب المادة

_ Rotation about fixed axis

→ Centroid (G)

$$\sum M_G = I_G \alpha$$

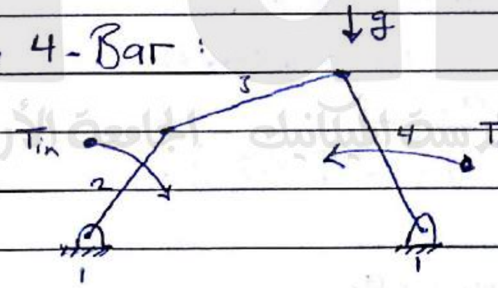
→ Non-Centroid (A)

$$\sum M_A = I_A \alpha$$

$$I_A = I_G + md^2$$

Note: parallel axis theo.
بنستخدمه اذا كان الجسم بدور حول محور ثاني

* 4-Bar:

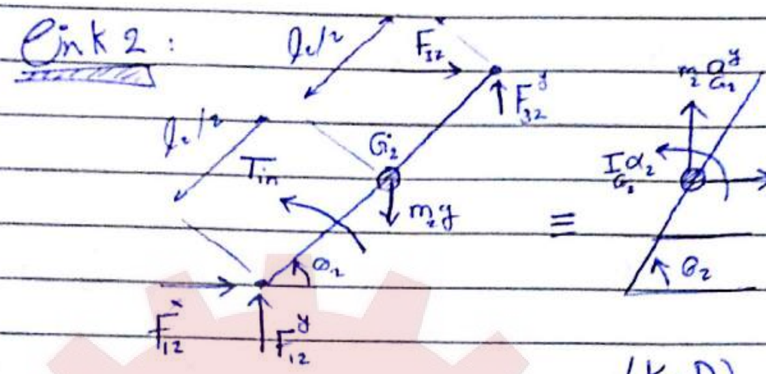


Given: Kinematic + masses.

_ Find: For a certain out put torque on link 4 (ex) find the necessary input torque on link 2 (ex) and the pin forces.

No.

Link 2 :



(K.D)

$$\xrightarrow{+}\sum F_x = \sum (F_x)_{eff.}$$

$$F_{12}^x + F_{32}^x = m_2 a_{G_2}^x \quad \text{------}(1)$$

$$+\uparrow \sum F_y = \sum (F_y)_{eff}$$

$$F_{12}^y + F_{32}^y - m_2 g = m_2 a_{G_2}^y \quad \text{------}(2)$$

$$\circlearrowleft + \sum M_{O_2} = \sum (M_{O_2})_{eff.}$$

$$T_{in} - m_2 g \frac{l_2}{2}\cos\theta_2 + F_{32}^y l_2 \cos\theta_2 - F_{32}^x l_2 \sin\theta_2 = I_{G_2}\alpha_2$$

$$+ m_2 a_{G_2}^x \frac{l_2}{2}\sin\theta_2 - m_2 a_{G_2}^x \frac{l_2}{2}\cos\theta_2$$

$$= I_{O_2}\alpha_2 \quad \text{----}(3)$$

$$** \quad \vec{a} = \underbrace{(\ddot{r} - r\omega^2)}_{a_r}\hat{u}_\theta + \underbrace{(r\alpha + 2\dot{r}\omega)}_{a_t}\hat{u}_{\theta+\pi/2}$$

$$\hat{u}_\theta = (\cos\theta\,\hat{i} + \sin\theta\,\hat{j}) \qquad \hat{u}_{\theta+\pi/2} = (-\sin\theta\,\hat{i} + \cos\theta\,\hat{j}).$$

$$= \underbrace{[a_r\cos\theta - a_t\sin\theta]}_{a_x}\hat{i} + \underbrace{[a_r\sin\theta + a_t\cos\theta]}_{a_y}\hat{j}$$

$$\rightarrow a_{G_2}^x = -\frac{l_2}{2}\omega_2^2\cos\theta_2 - \frac{l_2}{2}\alpha_2\sin\theta_2$$

$\ddot{r} = 0$

$-r\omega^2 = \frac{l_2}{2}\omega_2^2 \;\}\; a_r$

$r\alpha = \frac{l_2}{2}\alpha_2 \;\}\; a_t$

$2\dot{r}\omega = 0$

$$\rightarrow a_{G_2}^y = -\frac{l_2}{2}\omega_2^2\sin\theta_2 + \frac{l_2}{2}\alpha_2\cos\theta_2.$$

الإشارات
$\xrightarrow{}$ $I_c\alpha$

(x) $m_2 a^x_{G_2}\left(\frac{l_2}{2}\sin\theta_2\right) = m_2\frac{l_2}{2}\sin\theta_2\left(-\frac{l_2}{2}\omega_2^2\cos\theta_2 - \frac{l_2}{2}\alpha_2\sin\theta_2\right)$

$= -m_2\left(\frac{l_2}{2}\right)^2\omega_2^2\sin\theta_2\cos\theta_2 - m_2\left(\frac{l_2}{2}\right)^2\alpha_2\sin^2\theta_2$

(y) $m_2 a^y_{G_2}\left(\frac{l_2}{2}\right)\cos\theta_2 = m_2\frac{l_2}{2}\cos\theta_2\left(-\frac{l_2}{2}\omega_2^2\sin\theta_2 + \frac{l_2}{2}\alpha_2\cos\theta_2\right)$

$= -m_2\left(\frac{l_2}{2}\right)^2\omega_2^2\sin\theta_2\cos\theta_2 + m_2\left(\frac{l_2}{2}\right)^2\alpha_2\cos^2\theta_2$

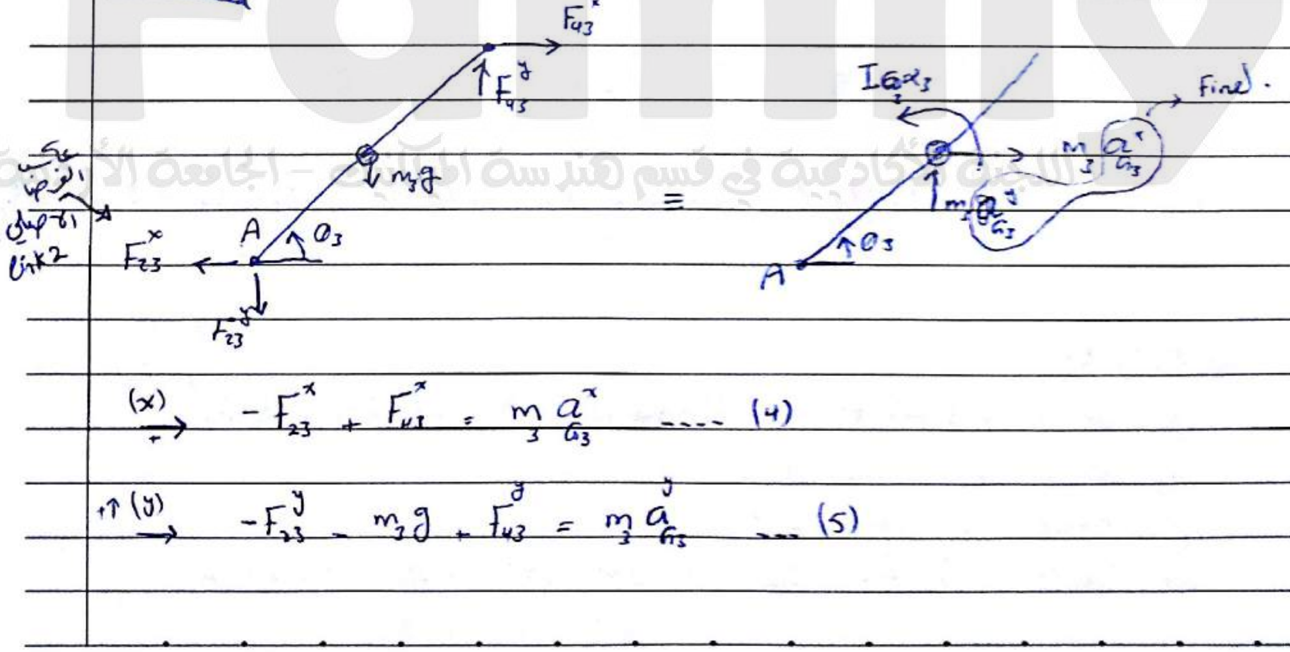
R.S (3) : $I_{G_2}\alpha_2 - m_2 a^x_{G_2}\frac{l_2}{2}\sin\theta_2 + m_2 a^y_{G_2}\frac{l_2}{2}\cos\theta_2$

$= I_{G_2}\alpha_2 + 0 + m\left(\frac{l_2}{2}\right)^2\alpha_2\left(\sin^2\theta_2 + \cos^2\theta_2\right)$

$= I_{G_2}\alpha_2 + m_2\left(\frac{l_2}{2}\right)^2\alpha_2 = \underbrace{\left[I_{G_2} + m\left(\frac{l_2}{2}\right)^2\right]}_{I_{O_2}}\alpha_2$

$\Rightarrow \boxed{I_{O_2}\alpha_2}$ #

Link 3:



(x) $\xrightarrow{+}$ $-F^x_{23} + F^x_{43} = m_3 a^x_{G_3}$ ---- (4)

$+\uparrow$ (y) $-F^y_{23} - m_3 g + F^y_{43} = m_3 a^y_{G_3}$ ---- (5)

No.

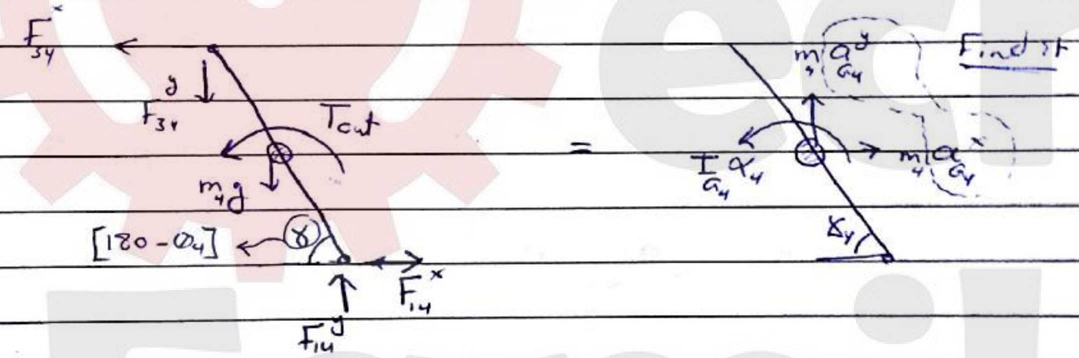
$$\circlearrowleft^{+} \sum M_A = \sum (M)_{eff}$$

← بدل M_A اسهل من M_B
لانه بـ Torq عند $_4$ معروف
ما اخذ M_{O_4} وصلت سهل حل
حالي كل.

$$-m_3 g\left(\frac{l_3}{2}\right)\cos\theta_3 + F_{43}^{y} l_3 \cos\theta_3 - F_{43}^{x} l_3 \sin\theta_3 = I_{G_3}\alpha_3 + m_3 a_{G_3}^{y}\left(\frac{l_3}{2}\right)\cos\theta_3 - m_3 a_{G_3}^{x}\left(\frac{l_3}{2}\right)\sin\theta_3 \quad ---(6)$$

$$\neq I_A \alpha_3$$ لانها مش Gip M

Link 4:



$$\xrightarrow{+} x: \; -F_{34}^{x} + F_{14}^{x} = m_4 a_{G_4}^{x} \quad ---(7)$$

$$+\uparrow y: \; -F_{34}^{y} - m_4 g + F_{14}^{y} = m_4 a_{G_4}^{y} \quad ---(8)$$

$$\circlearrowleft^{+} M_{O_4}: \; T_{out} + m_4 g\left(\frac{l_4}{2}\right)\cos\gamma_4 + F_{34}^{y} l_4 \cos\gamma_4 + F_{34}^{x} l_4 \sin\gamma_4 = I_{O_4}\alpha_4 \quad ---(9)$$

* Solution:

1. solve (6) and (4) simultaneasly to find F_{43}^{x} and F_{43}^{y}
2. solve (4) for F_{32}^{x}
3. solve (5) for F_{32}^{y}
4. solve (3) for T_{in}

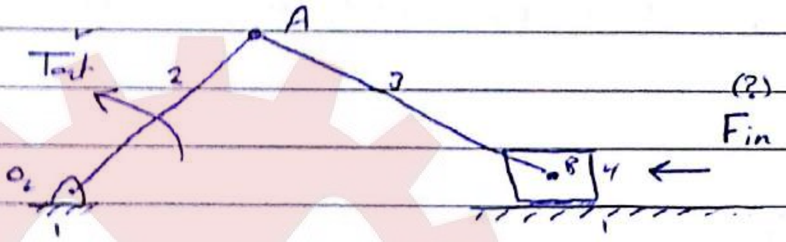
∴ انا بحتاج فقط لـ (4) معادلات
مشان اطلع T_{in} وما بحتاج
المعادلات الثانية إلا اذا طلب
مطاليب اخرى.

No.

(5) " (1) " F_{12}^x (7) " (7) " F_{14}^x

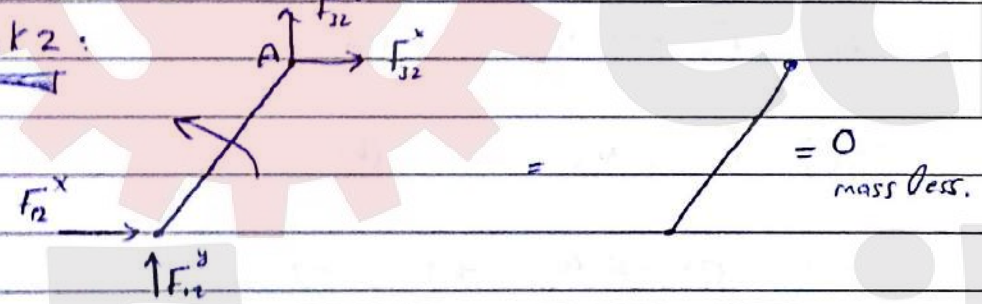
(6) " (2) " F_{12}^y (8) " (8) " F_{14}^y

** slider-crank :



for certine T_{out}, find F_{in}?
Assume links 2 and 3 are massless.

link 2 :



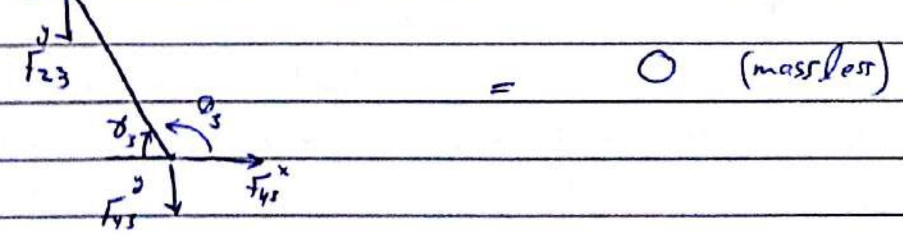
$\xrightarrow{+}$ x : $F_{12}^x + F_{32}^x = 0$ --- (1)

$+\uparrow$ y : $F_{12}^y + F_{32}^y = 0$ --- (2)

$+\circlearrowleft M_{O_2}$: $T_{out} + F_{32}^y\, l_2 \cos\theta_2 - F_{32}^x\, l_2 \sin\theta_2 = 0$ --- (3)

ابو known
لـ تعوض
الـ moment
دايماً

link 3 :



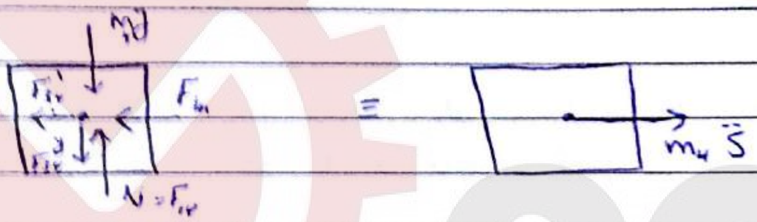
No. ____

$\xrightarrow{+} x: \; -F_{23}^x + F_{43}^x = 0$ --- (4)

$+\uparrow y: \; -F_{23}^y + F_{43}^y = 0$ --- (5)

$\circlearrowleft \sum M_{B}: \; F_{23}^x l_3 \sin\gamma_3 + F_{23}^y l_3 \cos\gamma_3 = 0$ --- (6)

Link 4:



$\xrightarrow{+} x: \; -F_{34}^x - F_{in} = m_4 \ddot{S}$ ---- (7)

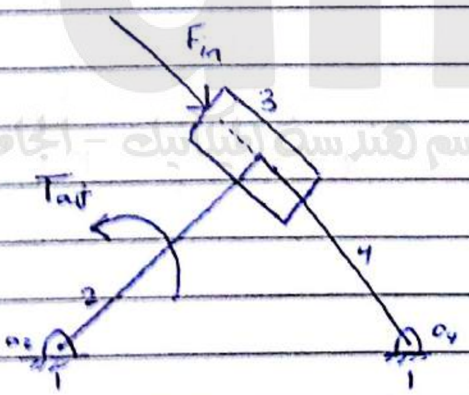
$+\uparrow y: \; -mg - F_{34}^y + N = 0$ --- (8)

Solu: solve (3) and (6) → F_{32}^x and F_{32}^y

" (4) → F_{43}^x

" (7) → F_{in}

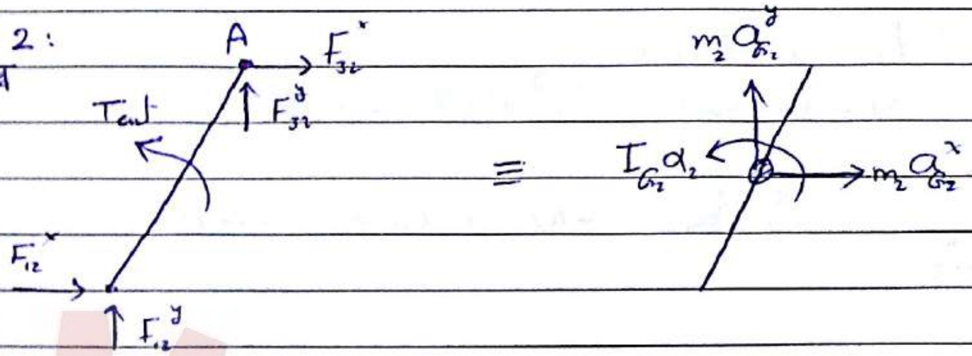
** **



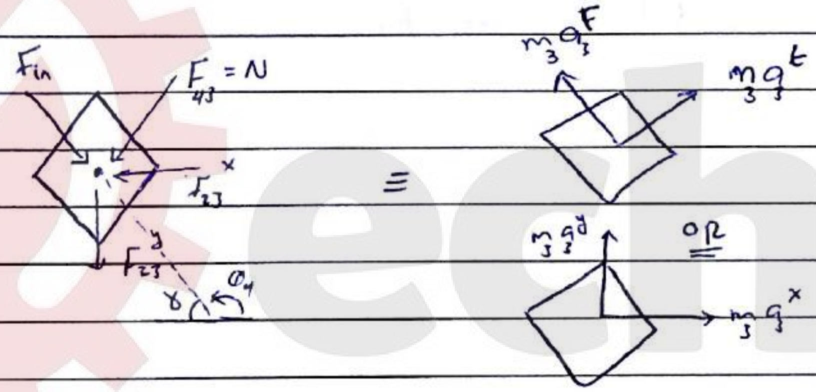
Find a relation between T_{out} and F_{in}. [Motion in horizontal plane] ?!

No.

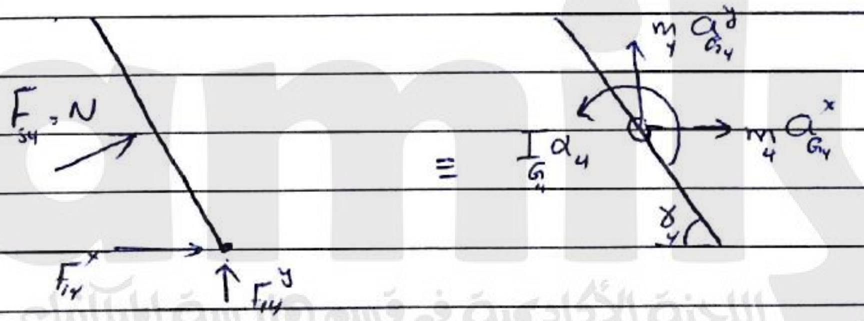
Link 2:



Link 3:



Link 4:



equ.

Link 2: $\sum M_{O_2} = \sum (M)_{eff}$

$$T_{out} + F_{32}^y l_2 \cos\theta_2 - F_{32}^x l_2 \sin\theta_2 = I_{O_2}\alpha_2 \quad ---(1)$$

equ.

Link 3: $\uparrow \sum F_r = \sum (F_r)_{eff}$

$$-F_{in} + F_{23}^x \cos\gamma_4 - F_{23}^y \sin\gamma_4 = m_3 a_3^r \quad ---(2)$$

No.

$\nearrow \sum F_t = \sum (F_t)_{eff}$

$-N - F_{23}^x \sin \gamma_4 - F_{23}^y \cos \gamma_4 = m_3 a_3^t \quad \text{--- (3)}$

equ.
<u>link 4</u> : $\circlearrowleft M_{a_x}: \quad -Ns = I_{o_4} \alpha_4 \quad \text{--- (4)}$

$\rightarrow$ solve (4) $\rightarrow N$

solve (3) and (1) $\rightarrow F_{32}^x, F_{32}^y$

solve (2) $\rightarrow F_{in}$