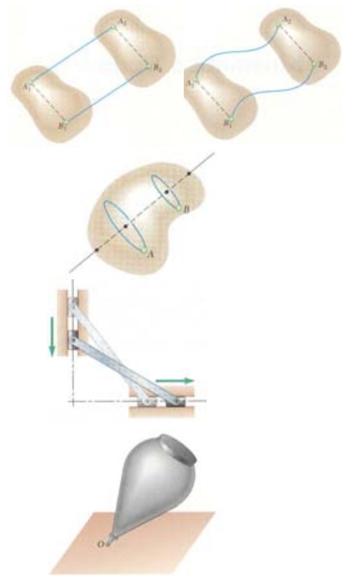
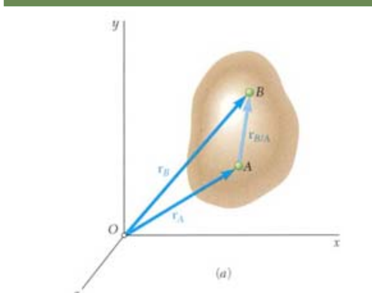
Ch. 15 Kinematics of Rigid Bodies

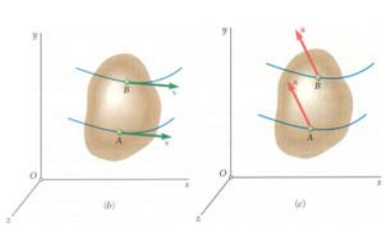


- Kinematics of rigid bodies: relations between time and the positions, velocities, and accelerations of the particles forming a rigid body.
- Classification of rigid body motions:
  - translation:
    - rectilinear translation
    - curvilinear translation
  - rotation about a fixed axis
  - general plane motion
  - motion about a fixed point
  - general motion

Translation



(a)



(b) (c)

- Consider rigid body in translation:
  - direction of any straight line inside the body is constant,
  - all particles forming the body move in parallel lines.
- For any two particles in the body,

$$\vec{r}_B = \vec{r}_A + \vec{r}_{B/A}$$

- Differentiating with respect to time,

$$\dot{\vec{r}}_B = \dot{\vec{r}}_A + \dot{\vec{r}}_{B/A} = \dot{\vec{r}}_A$$

$$\vec{v}_B = \vec{v}_A$$

All particles have the same velocity.

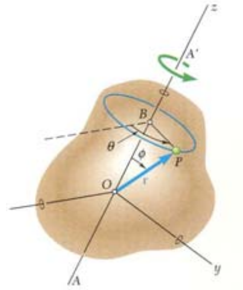
- Differentiating with respect to time again,

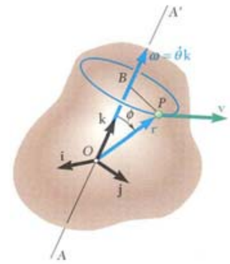
$$\ddot{\vec{r}}_B = \ddot{\vec{r}}_A + \ddot{\vec{r}}_{B/A} = \ddot{\vec{r}}_A$$

$$\vec{a}_B = \vec{a}_A$$

All particles have the same acceleration.

Rotation About a Fixed Axis. Velocity





- Consider rotation of rigid body about a fixed axis *AA'*

- Velocity vector $\vec{v} = d\vec{r}/dt$ of the particle *P* is tangent to the path with magnitude $v = ds/dt$

$$\Delta s = (BP)\Delta\theta = (r\sin\phi)\Delta\theta$$

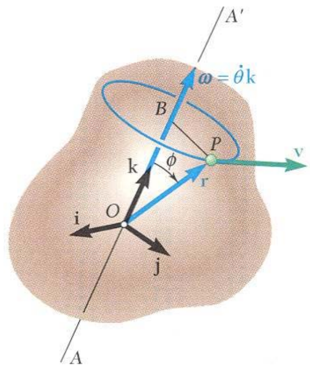
$$v = \frac{ds}{dt} = \lim_{\Delta t \to 0}(r\sin\phi)\frac{\Delta\theta}{\Delta t} = r\dot{\theta}\sin\phi$$

- The same result is obtained from

$$\vec{v} = \frac{d\vec{r}}{dt} = \vec{\omega}\times\vec{r}$$

$$\vec{\omega} = \omega\vec{k} = \dot{\theta}\vec{k} = \text{angular velocity}$$

Rotation About a Fixed Axis. Acceleration



- Differentiating to determine the acceleration,

$$\vec{a} = \frac{d\vec{v}}{dt} = \frac{d}{dt}(\vec{\omega}\times\vec{r})$$

$$= \frac{d\vec{\omega}}{dt}\times\vec{r} + \vec{\omega}\times\frac{d\vec{r}}{dt}$$

$$= \frac{d\vec{\omega}}{dt}\times\vec{r} + \vec{\omega}\times\vec{v}$$

- $\frac{d\vec{\omega}}{dt} = \vec{\alpha} = \text{angular acceleration}$

$$= \alpha\vec{k} = \dot{\omega}\vec{k} = \ddot{\theta}\vec{k}$$

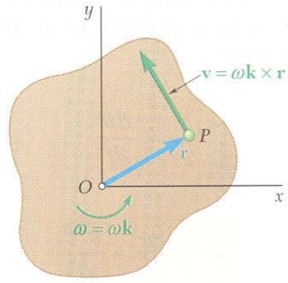
- Acceleration of *P* is combination of two vectors,

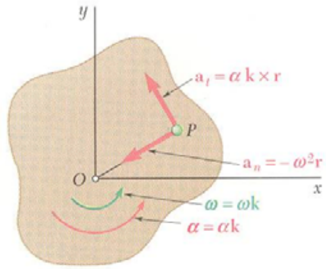
$$\vec{a} = \vec{\alpha}\times\vec{r} + \vec{\omega}\times\vec{\omega}\times\vec{r}$$

$$\vec{\alpha}\times\vec{r} = \text{tangential acceleration component}$$

$$\vec{\omega}\times\vec{\omega}\times\vec{r} = \text{radial acceleration component}$$

Rotation About a Fixed Axis. Representative Slab





- Consider the motion of a representative slab in a plane perpendicular to the axis of rotation.
- Velocity of any point *P* of the slab,

$$\vec{v} = \vec{\omega} \times \vec{r} = \omega \vec{k} \times \vec{r}$$
$$v = r\omega$$

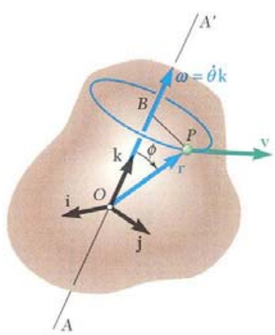
- Acceleration of any point *P* of the slab,

$$\vec{a} = \vec{\alpha} \times \vec{r} + \vec{\omega} \times \vec{\omega} \times \vec{r}$$
$$= \alpha \vec{k} \times \vec{r} - \omega^2 \vec{r}$$

- Resolving the acceleration into tangential and normal components,

$$\vec{a}_t = \alpha \vec{k} \times \vec{r} \qquad a_t = r\alpha$$
$$\vec{a}_n = -\omega^2 \vec{r} \qquad a_n = r\omega^2$$

Equations Defining the Rotation of a Rigid Body About a Fixed Axis



- Motion of a rigid body rotating around a fixed axis is often specified by the type of angular acceleration.
- Recall $\omega = \dfrac{d\theta}{dt}$ or $dt = \dfrac{d\theta}{\omega}$

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2} = \omega \frac{d\omega}{d\theta}$$

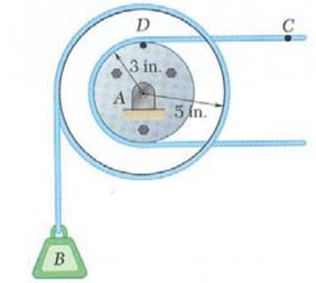
- *Uniform Rotation*, $\alpha = 0$:

$$\theta = \theta_0 + \omega t$$

- *Uniformly Accelerated Rotation*, α = constant:

$$\omega = \omega_0 + \alpha t$$
$$\theta = \theta_0 + \omega_0 t + \tfrac{1}{2}\alpha t^2$$
$$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$$

Sample Problem 5.1



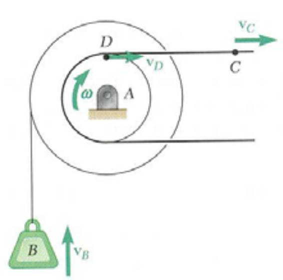
Cable C has a constant acceleration of 9 in/s^2 and an initial velocity of 12 in/s, both directed to the right.

Determine *(a)* the number of revolutions of the pulley in 2 s, *(b)* the velocity and change in position of the load B after 2 s, and *(c)* the acceleration of the point D on the rim of the inner pulley at t = 0.

SOLUTION:

- Due to the action of the cable, the tangential velocity and acceleration of D are equal to the velocity and acceleration of C. Calculate the initial angular velocity and acceleration.
- Apply the relations for uniformly accelerated rotation to determine the velocity and angular position of the pulley after 2 s.
- Evaluate the initial tangential and normal acceleration components of D.

Sample Problem 5.1



SOLUTION:

- The tangential velocity and acceleration of D are equal to the velocity and acceleration of C.

$$(\vec{v}_D)_0 = (\vec{v}_C)_0 = 12\,\text{in./s} \rightarrow \qquad (\vec{a}_D)_t = \vec{a}_C = 9\,\text{in./s} \rightarrow$$

$$(v_D)_0 = r\omega_0 \qquad (a_D)_t = r\alpha$$

$$\omega_0 = \frac{(v_D)_0}{r} = \frac{12}{3} = 4\,\text{rad/s} \qquad \alpha = \frac{(a_D)_t}{r} = \frac{9}{3} = 3\,\text{rad/s}^2$$

- Apply the relations for uniformly accelerated rotation to determine velocity and angular position of pulley after 2 s.

$$\omega = \omega_0 + \alpha t = 4\,\text{rad/s} + \left(3\,\text{rad/s}^2\right)(2\,\text{s}) = 10\,\text{rad/s}$$

$$\theta = \omega_0 t + \tfrac{1}{2}\alpha t^2 = (4\,\text{rad/s})(2\,\text{s}) + \tfrac{1}{2}\left(3\,\text{rad/s}^2\right)(2\,\text{s})^2$$

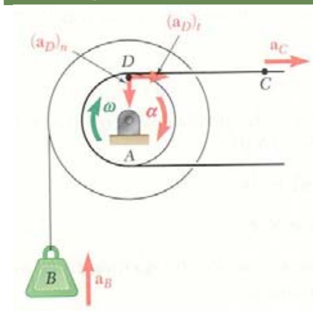
$$= 14\,\text{rad}$$

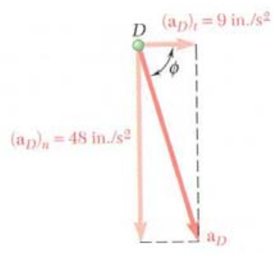
$$N = (14\,\text{rad})\left(\frac{1\,\text{rev}}{2\pi\,\text{rad}}\right) = \text{number of revs} \qquad \boxed{N = 2.23\,\text{rev}}$$

$$v_B = r\omega = (5\,\text{in.})(10\,\text{rad/s}) \qquad \boxed{\vec{v}_B = 50\,\text{in./s} \uparrow}$$

$$\Delta y_B = r\theta = (5\,\text{in.})(14\,\text{rad}) \qquad \boxed{\Delta y_B = 70\,\text{in.}}$$

Sample Problem 5.1





- Evaluate the initial tangential and normal acceleration components of *D*.

$$(\vec{a}_D)_t = \vec{a}_C = 9\,\text{in./s} \rightarrow$$

$$(a_D)_n = r_D\omega_0^2 = (3\,\text{in.})(4\,\text{rad/s})^2 = 48\,\text{in/s}^2$$

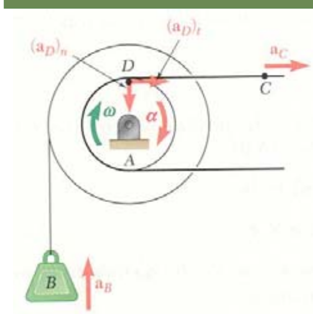
$$\boxed{(\vec{a}_D)_t = 9\,\text{in./s}^2 \rightarrow \qquad (\vec{a}_D)_n = 48\,\text{in./s}^2 \downarrow}$$

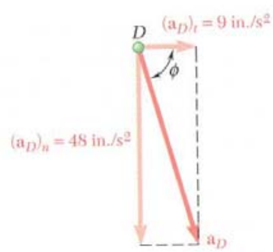
Magnitude and direction of the total acceleration,

$$a_D = \sqrt{(a_D)_t^2 + (a_D)_n^2} = \sqrt{9^2 + 48^2} \qquad \boxed{a_D = 48.8\,\text{in./s}^2}$$

$$\tan\phi = \frac{(a_D)_n}{(a_D)_t} = \frac{48}{9} \qquad \boxed{\phi = 79.4°}$$

Example Problem





- **Evaluate the initial tangential and normal acceleration components of *D*.**

$$(\vec{a}_D)_t = \vec{a}_C = 9\,\text{in./s} \rightarrow$$

$$(a_D)_n = r_D\omega_0^2 = (3\,\text{in.})(4\,\text{rad/s})^2 = 48\,\text{in/s}^2$$

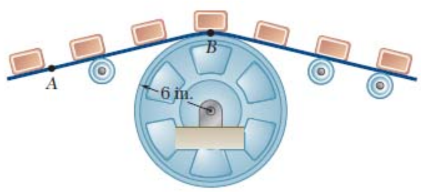
$$\boxed{(\vec{a}_D)_t = 9\,\text{in./s}^2 \rightarrow \qquad (\vec{a}_D)_n = 48\,\text{in./s}^2 \downarrow}$$

Magnitude and direction of the total acceleration,

$$a_D = \sqrt{(a_D)_t^2 + (a_D)_n^2} = \sqrt{9^2 + 48^2} \qquad \boxed{a_D = 48.8\,\text{in./s}^2}$$

$$\tan\phi = \frac{(a_D)_n}{(a_D)_t} = \frac{48}{9} \qquad \boxed{\phi = 79.4°}$$

Example Problem



A series of small machine components being moved by a conveyor belt pass over a 6-in.-radius idler pulley. At the instant shown, the velocity of point *A* is 15 in./s to the left and its acceleration is 9 in./s^2 to the right. Determine (*a*) the angular velocity and angular acceleration of the idler pulley, (*b*) the total acceleration of the machine component at *B*.

<u>SOLUTION</u>:

- Using the linear velocity and accelerations, calculate the angular velocity and acceleration.
- Using the angular velocity, determine the normal acceleration.
- Determine the total acceleration using the tangential and normal acceleration components of *B*.

Example Problem

Find the angular velocity of the idler pulley using the linear velocity at B.

$$v = r\omega$$

$$15\text{ in./s} = (6\text{ in.})\omega$$

$$\boxed{\boldsymbol{\omega} = 2.50\text{ rad/s}}$$

Find the angular velocity of the idler pulley using the linear velocity at B.

$$a = r\alpha$$

$$9\text{ in./s}^2 = (6\text{ in.})\alpha$$

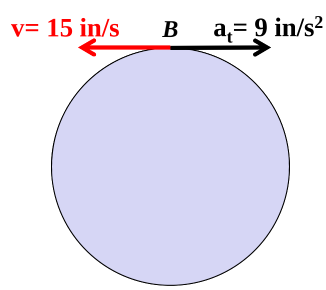
$$\boxed{\boldsymbol{\alpha} = 1.500\text{ rad/s}^2}$$

Find the normal acceleration of point *B*.

$$a_n = r\omega^2$$

$$= (6\text{ in.})(2.5\text{ rad/s})^2$$

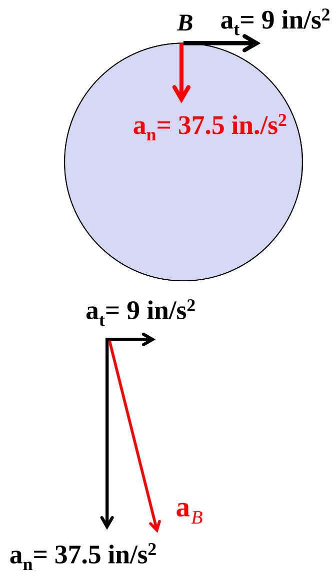
$$\mathbf{a}_n = 37.5\text{ in./s}^2$$



What is the direction of the normal acceleration of point *B*?

Downwards, towards the center

Example Problem



Find the total acceleration of the machine component at point *B*.

$\mathbf{a}_t = 9.0 \text{ in./s}^2 \qquad \mathbf{a}_n = 37.5 \text{ in./s}^2$

Calculate the magnitude

$$|\mathbf{a}| = \sqrt{9.0^2 + 37.5^2} = 38.6 \text{ in./s}^2$$

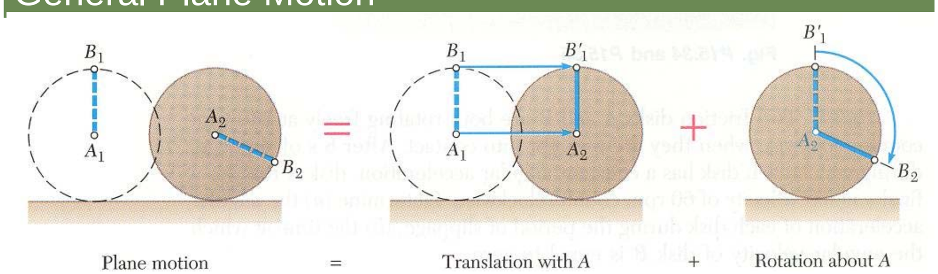
Calculate the angle from the horizontal

$$\theta = \arctan\left(\frac{37.5}{9.0}\right) = 76.5^{\circ}$$

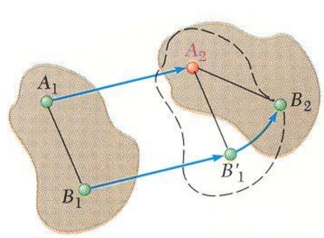
Combine for a final answer

$$\boxed{\mathbf{a}_B = 38.6 \text{ in./s}^2 \quad 76.5^{\circ}}$$

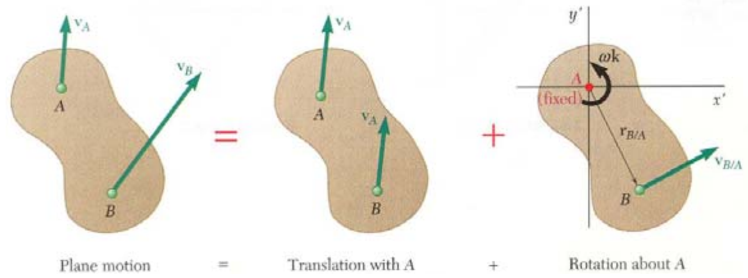
General Plane Motion

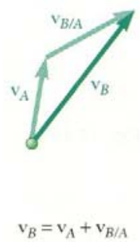


- *General plane motion* is neither a translation nor a rotation.
- General plane motion can be considered as the *sum* of a translation and rotation.
- Displacement of particles A and B to A_2 and B_2 can be divided into two parts:
  - translation to A_2 and B_1'
  - rotation of B_1' about A_2 to B_2



Absolute and Relative Velocity in Plane Motion





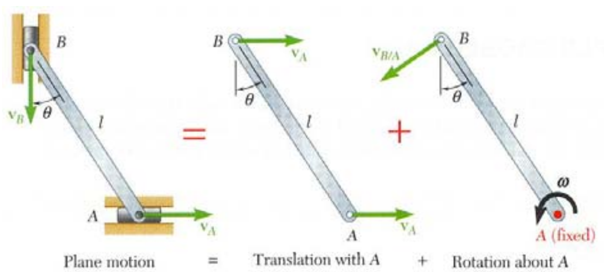
- Any plane motion can be replaced by a translation of an arbitrary reference point *A* and a simultaneous rotation about *A*.

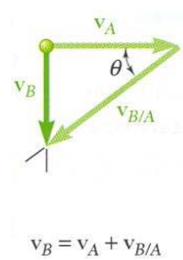
$$\vec{v}_B = \vec{v}_A + \vec{v}_{B/A}$$

$$\vec{v}_{B/A} = \omega\vec{k} \times \vec{r}_{B/A} \qquad v_{B/A} = r\omega$$

$$\vec{v}_B = \vec{v}_A + \omega\vec{k} \times \vec{r}_{B/A}$$

Absolute and Relative Velocity in Plane Motion



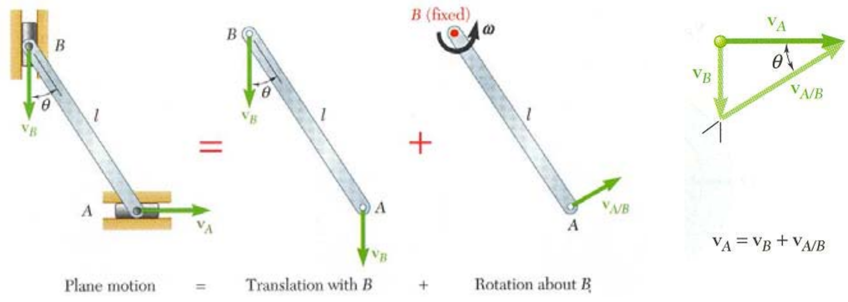


- Assuming that the velocity v_A of end *A* is known, wish to determine the velocity v_B of end *B* and the angular velocity ω in terms of v_A, *l*, and θ.
- The direction of v_B and $v_{B/A}$ are known. Complete the velocity diagram.

$$\frac{v_B}{v_A} = \tan\theta \qquad \frac{v_A}{v_{B/A}} = \frac{v_A}{l\omega} = \cos\theta$$

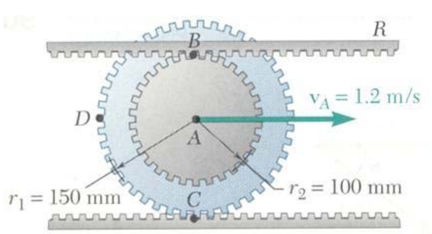
$$v_B = v_A \tan\theta \qquad \omega = \frac{v_A}{l\cos\theta}$$

Absolute and Relative Velocity in Plane Motion



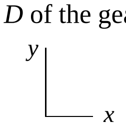
- Selecting point B as the reference point and solving for the velocity v_A of end A and the angular velocity ω leads to an equivalent velocity triangle.
- $v_{A/B}$ has the same magnitude but opposite sense of $v_{B/A}$. The sense of the relative velocity is dependent on the choice of reference point.
- Angular velocity ω of the rod in its rotation about B is the same as its rotation about A. Angular velocity is not dependent on the choice of reference point.

Sample Problem 15.2



The double gear rolls on the stationary lower rack: the velocity of its center is 1.2 m/s.

Determine *(a)* the angular velocity of the gear, and *(b)* the velocities of the upper rack R and point D of the gear.



<u>SOLUTION</u>:

- The displacement of the gear center in one revolution is equal to the outer circumference.

  For $x_A > 0$ (moves to right), $\omega < 0$ (rotates clockwise).

$$\frac{x_A}{2\pi r} = -\frac{\theta}{2\pi} \qquad x_A = -r_1\theta$$

Differentiate to relate the translational and angular velocities.

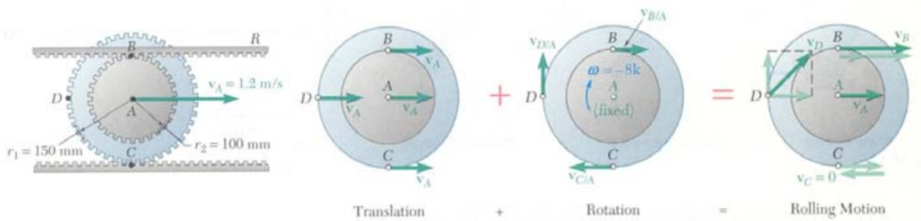
$$\boxed{\vec{\omega} = \omega\vec{k} = -(8\,\mathrm{rad/s})\vec{k}}$$

$$v_A = -r_1\omega$$

$$\omega = -\frac{v_A}{r_1} = -\frac{1.2\,\mathrm{m/s}}{0.150\ \mathrm{m}}$$

Sample Problem 15.2

- For any point P on the gear, $\vec{v}_P = \vec{v}_A + \vec{v}_{P/A} = \vec{v}_A + \omega\vec{k} \times \vec{r}_{P/A}$



Velocity of the upper rack is equal to velocity of point B:

$$\vec{v}_R = \vec{v}_B = \vec{v}_A + \omega\vec{k} \times \vec{r}_{B/A}$$
$$= (1.2\,\mathrm{m/s})\vec{i} + (8\,\mathrm{rad/s})\vec{k} \times (0.10\,\mathrm{m})\vec{j}$$
$$= (1.2\,\mathrm{m/s})\vec{i} + (0.8\,\mathrm{m/s})\vec{i}$$

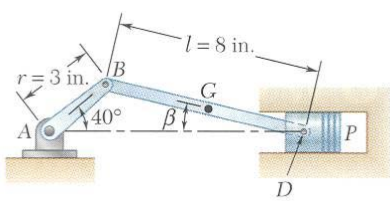
$$\boxed{\vec{v}_R = (2\,\mathrm{m/s})\vec{i}}$$

Velocity of the point D:

$$\vec{v}_D = \vec{v}_A + \omega\vec{k} \times \vec{r}_{D/A}$$
$$= (1.2\,\mathrm{m/s})\vec{i} + (8\,\mathrm{rad/s})\vec{k} \times (-0.150\,\mathrm{m})\vec{i}$$

$$\boxed{\begin{aligned}\vec{v}_D &= (1.2\,\mathrm{m/s})\vec{i} + (1.2\,\mathrm{m/s})\vec{j} \\ v_D &= 1.697\,\mathrm{m/s}\end{aligned}}$$

Sample Problem 15.3



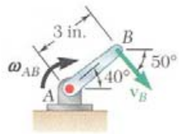
The crank AB has a constant clockwise angular velocity of 2000 rpm.

For the crank position indicated, determine *(a)* the angular velocity of the connecting rod BD, and *(b)* the velocity of the piston P.

SOLUTION:

- Will determine the absolute velocity of point D with
$$\vec{v}_D = \vec{v}_B + \vec{v}_{D/B}$$
- The velocity $\vec{v}_B$ is obtained from the given crank rotation data.
- The directions of the absolute velocity $\vec{v}_D$ and the relative velocity $\vec{v}_{D/B}$ are determined from the problem geometry.
- The unknowns in the vector expression are the velocity magnitudes v_D and $v_{D/B}$ which may be determined from the corresponding vector triangle.
- The angular velocity of the connecting rod is calculated from $v_{D/B}$.

Sample Problem 15.3



SOLUTION:

- Will determine the absolute velocity of point D with

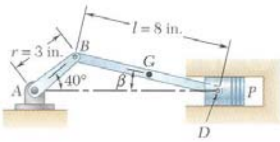
$$\vec{v}_D = \vec{v}_B + \vec{v}_{D/B}$$

- The velocity $\vec{v}_B$ is obtained from the crank rotation data.

$$\omega_{AB} = \left(2000\frac{\text{rev}}{\text{min}}\right)\left(\frac{\text{min}}{60\text{s}}\right)\left(\frac{2\pi\,\text{rad}}{\text{rev}}\right) = 209.4\ \text{rad/s}$$

$$v_B = (AB)\omega_{AB} = (3\text{in.})(209.4\ \text{rad/s})$$

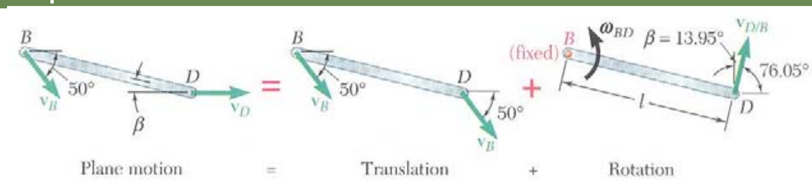
The velocity direction is as shown.

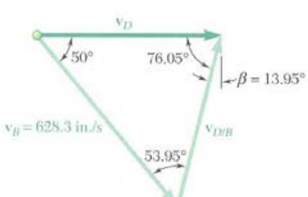


- The direction of the absolute velocity $\vec{v}_D$ is horizontal. The direction of the relative velocity $\vec{v}_{D/B}$ is perpendicular to BD. Compute the angle between the horizontal and the connecting rod from the law of sines.

$$\frac{\sin 40°}{8\text{in.}} = \frac{\sin\beta}{3\text{in.}} \qquad \beta = 13.95°$$

Sample Problem 15.3





$$\vec{v}_D = \vec{v}_B + \vec{v}_{D/B}$$

- Determine the velocity magnitudes v_D and $v_{D/B}$ from the vector triangle.

$$\frac{v_D}{\sin 53.95°} = \frac{v_{D/B}}{\sin 50°} = \frac{628.3\text{in./s}}{\sin 76.05°}$$

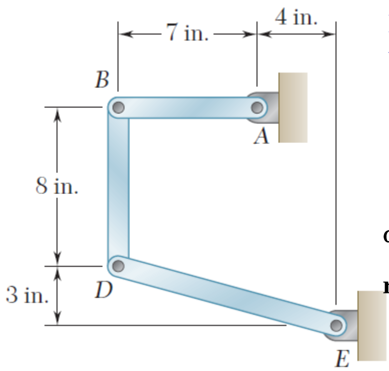
$$v_D = 523.4\text{in./s} = 43.6\,\text{ft/s} \qquad \boxed{v_P = v_D = 43.6\,\text{ft/s}}$$

$$v_{D/B} = 495.9\text{in./s}$$

$$v_{D/B} = l\omega_{BD}$$

$$\omega_{BD} = \frac{v_{D/B}}{l} = \frac{495.9\text{in./s}}{8\,\text{in.}} = 62.0\ \text{rad/s} \qquad \boxed{\vec{\omega}_{BD} = (62.0\ \text{rad/s})\vec{k}}$$

Example Problem



Determine $\mathbf{v}_B$ with respect to A, then work your way along the linkage to point E.

Write $\mathbf{v}_B$ in terms of point A, calculate $\mathbf{v}_B$.

$$\mathbf{v}_B = \cancel{\mathbf{v}_A} + \boldsymbol{\omega}_{AB} \times \mathbf{r}_{B/A}$$

$$\boldsymbol{\omega}_{AB} = -(4 \text{ rad/s})\mathbf{k}$$

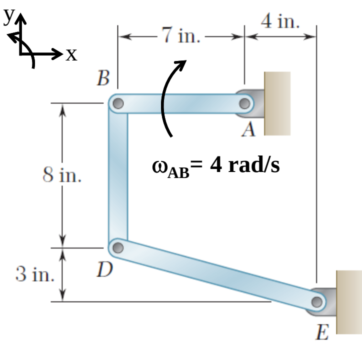
$$\mathbf{r}_{B/A} = -(7 \text{ in.})\mathbf{i} \qquad \mathbf{v}_B = \boldsymbol{\omega}_{AB} \times r_{B/A} = (-4\mathbf{k}) \times (-7\mathbf{i})$$

$$\mathbf{v}_B = (28 \text{ in./s})\mathbf{j}$$

In the position shown, bar *AB* has an angular velocity of 4 rad/s clockwise. Determine the angular velocity of bars *BD* and *DE*.

$\mathbf{v}_D$,

Example Problem



Determine $\mathbf{v}_D$ with respect to B.

$$\boldsymbol{\omega}_{BD} = \omega_{BD}\mathbf{k} \qquad \mathbf{r}_{D/B} = -(8 \text{ in.})\mathbf{j}$$

$$\mathbf{v}_D = \mathbf{v}_B + \boldsymbol{\omega}_{BD} \times \mathbf{r}_{D/B} = 28\mathbf{j} + (\omega_{BD}\mathbf{k}) \times (-8\mathbf{j})$$

$$\mathbf{v}_D = 28\mathbf{j} + 8\omega_{BD}\mathbf{i}$$

Determine $\mathbf{v}_D$ with respect to E, then equate it to equation above.

$$\boldsymbol{\omega}_{DE} = \omega_{DE}\mathbf{k} \qquad \mathbf{r}_{D/E} = -(11 \text{ in.})\mathbf{i} + (3 \text{ in.})\mathbf{j}$$

$$\mathbf{v}_D = \boldsymbol{\omega}_{DE} \times \mathbf{r}_{D/E} = (\omega_{DE}\mathbf{k}) \times (-11\mathbf{i} + 3\mathbf{j})$$

$$\mathbf{v}_D = -11\omega_{DE}\mathbf{j} - 3\omega_{DE}\mathbf{i}$$

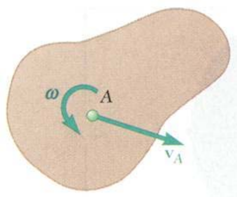
Equating components of the two expressions for $\mathbf{v}_D$

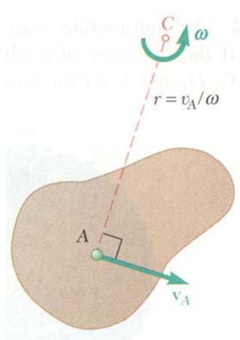
$$\text{j:} \quad 28 = -11\omega_{DE} \qquad \omega_{DE} = -2.5455 \text{ rad/s}$$

$$\mathbf{i}: \quad 8\omega_{BD} = -3\omega_{DE} \qquad \omega_{BD} = -\frac{3}{8}\omega_{BD}$$

$$\boxed{\begin{array}{l} \boldsymbol{\omega}_{DE} = 2.55 \text{ rad/s} \\ \boldsymbol{\omega}_{BD} = 0.955 \text{ rad/s} \end{array}}$$

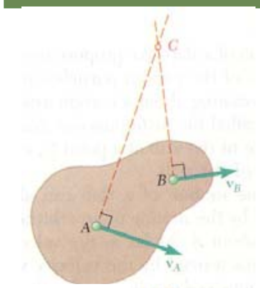
Instantaneous Center of Rotation in Plane Motion

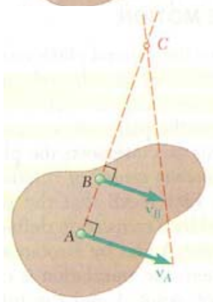




- Plane motion of all particles in a slab can always be replaced by the translation of an arbitrary point *A* and a rotation about *A* with an angular velocity that is independent of the choice of *A*.
- The same translational and rotational velocities at *A* are obtained by allowing the slab to rotate with the same angular velocity about the point *C* on a perpendicular to the velocity at *A*.
- The velocity of all other particles in the slab are the same as originally defined since the angular velocity and translational velocity at *A* are equivalent.
- As far as the velocities are concerned, the slab seems to rotate about the *instantaneous center of rotation C*.

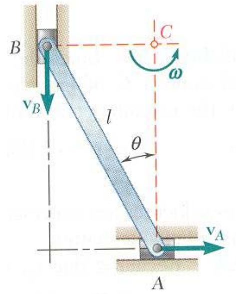
Instantaneous Center of Rotation in Plane Motion





- If the velocity at two points *A* and *B* are known, the instantaneous center of rotation lies at the intersection of the perpendiculars to the velocity vectors through *A* and *B* .
- If the velocity vectors are parallel, the instantaneous center of rotation is at infinity and the angular velocity is zero.
- If the velocity vectors at *A* and *B* are perpendicular to the line *AB*, the instantaneous center of rotation lies at the intersection of the line *AB* with the line joining the extremities of the velocity vectors at *A* and *B*.
- If the velocity magnitudes are equal, the instantaneous center of rotation is at infinity and the angular velocity is zero.

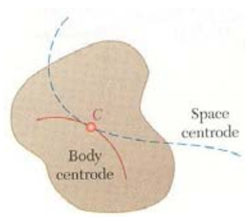
Instantaneous Center of Rotation in Plane Motion



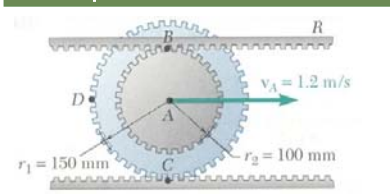
- The instantaneous center of rotation lies at the intersection of the perpendiculars to the velocity vectors through A and B .

$$\omega = \frac{v_A}{AC} = \frac{v_A}{l\cos\theta} \qquad v_B = (BC)\omega = (l\sin\theta)\frac{v_A}{l\cos\theta}$$
$$= v_A \tan\theta$$

- The velocities of all particles on the rod are as if they were rotated about *C.*
- The particle at the center of rotation has zero velocity.
- The particle coinciding with the center of rotation changes with time and the acceleration of the particle at the instantaneous center of rotation is not zero.
- The trace of the locus of the center of rotation on the body is the body centrode and in space is the space centrode.

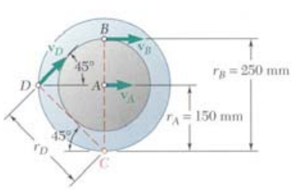


Sample Problem 15.4



The double gear rolls on the stationary lower rack: the velocity of its center is 1.2 m/s.

Determine *(a)* the angular velocity of the gear, and *(b)* the velocities of the upper rack *R* and point *D* of the gear.



<u>SOLUTION</u>:

- The point C is in contact with the stationary lower rack and, instantaneously, has zero velocity. It must be the location of the instantaneous center of rotation.

$$v_A = r_A\omega \qquad \omega = \frac{v_A}{r_A} = \frac{1.2\,\text{m/s}}{0.15\,\text{m}} = 8\,\text{rad/s}$$

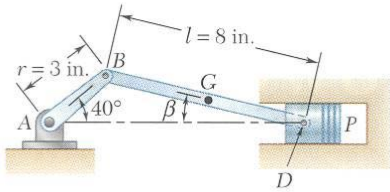
$$v_R = v_B = r_B\omega = (0.25\,\text{m})(8\,\text{rad/s})$$

$$\boxed{\vec{v}_R = (2\,\text{m/s})\vec{i}}$$

$$r_D = (0.15\,\text{m})\sqrt{2} = 0.2121\,\text{m}$$
$$v_D = r_D\omega = (0.2121\,\text{m})(8\,\text{rad/s})$$

$$\boxed{\begin{aligned} v_D &= 1.697\,\text{m/s} \\ \vec{v}_D &= \left(1.2\vec{i} + 1.2\vec{j}\right)(\text{m/s}) \end{aligned}}$$

Sample Problem 15.5



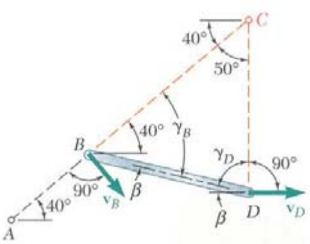
The crank *AB* has a constant clockwise angular velocity of 2000 rpm.

For the crank position indicated, determine *(a)* the angular velocity of the connecting rod *BD*, and *(b)* the velocity of the piston *P*.

SOLUTION:

- Determine the velocity at *B* from the given crank rotation data.
- The direction of the velocity vectors at *B* and *D* are known. The instantaneous center of rotation is at the intersection of the perpendiculars to the velocities through *B* and *D*.
- Determine the angular velocity about the center of rotation based on the velocity at *B*.
- Calculate the velocity at *D* based on its rotation about the instantaneous center of rotation.

Sample Problem 15.5



$$\gamma_B = 40° + \beta = 53.95°$$
$$\gamma_D = 90° - \beta = 76.05°$$

$$\frac{BC}{\sin 76.05°} = \frac{CD}{\sin 53.95°} = \frac{8\text{ in.}}{\sin 50°}$$

$$BC = 10.14\text{ in.} \quad CD = 8.44\text{ in.}$$

SOLUTION:

- From Sample Problem 15.3,

$$\vec{v}_B = (403.9\vec{i} - 481.3\vec{j})(\text{in./s}) \qquad v_B = 628.3\text{in./s}$$
$$\beta = 13.95°$$

- The instantaneous center of rotation is at the intersection of the perpendiculars to the velocities through *B* and *D*.
- Determine the angular velocity about the center of rotation based on the velocity at *B.*

$$v_B = (BC)\omega_{BD}$$

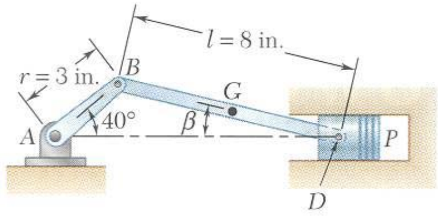
$$\omega_{BD} = \frac{v_B}{BC} = \frac{628.3\text{in./s}}{10.14\text{ in.}} \qquad \boxed{\omega_{BD} = 62.0\text{rad/s}}$$

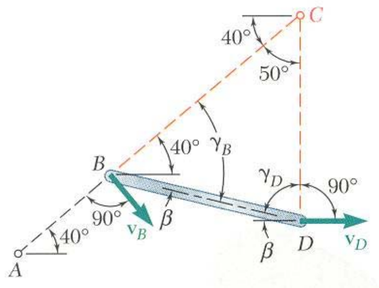
- Calculate the velocity at *D* based on its rotation about the instantaneous center of rotation.

$$v_D = (CD)\omega_{BD} = (8.44\text{ in.})(62.0\text{rad/s})$$

$$\boxed{v_P = v_D = 523\text{in./s} = 43.6\text{ft/s}}$$

Instantaneous Center of Zero Velocity

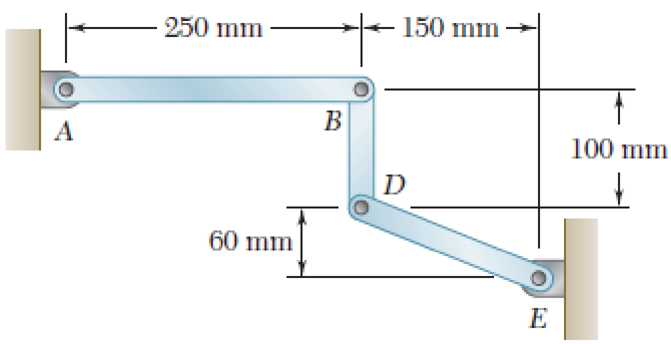




What happens to the location of the instantaneous center of velocity if the crankshaft angular velocity increases from 2000 rpm in the previous problem to 3000 rpm?

What happens to the location of the instantaneous center of velocity if the angle β is 0?

Example Problem



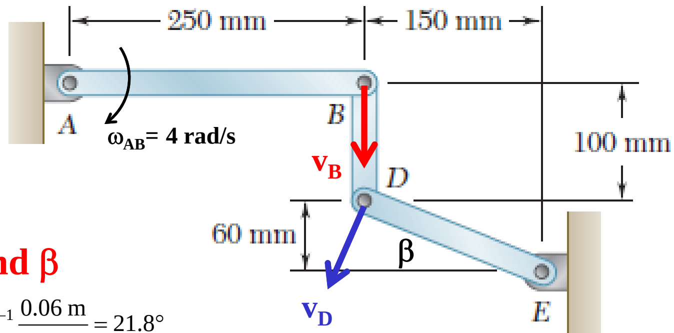
In the position shown, bar *AB* has an angular velocity of 4 rad/s clockwise. Determine the angular velocity of bars *BD* and *DE*.

Example Problem

What is the velocity of B? $\mathbf{v}_B = (AB)\omega_{AB} = (0.25\text{ m})(4\text{ rad/s}) = 1\text{ m/s}$

What direction is the velocity of B?

What direction is the velocity of D?

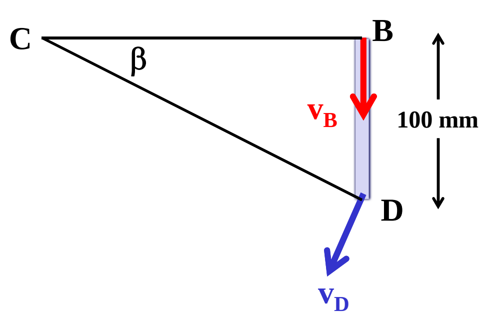


Find β

$$\beta = \tan^{-1}\frac{0.06\text{ m}}{0.15\text{ m}} = 21.8°$$

Example Problem

Locate instantaneous center C at intersection of lines drawn perpendicular to $\mathbf{v}_B$ and $\mathbf{v}_D$.



Find distances BC and DC

$$BC = \frac{0.1\text{ m}}{\tan\beta} = \frac{0.1\text{ m}}{\tan 21.8?} = 0.25\text{ m}$$

$$DC = \frac{0.25\text{ m}}{\cos\beta} = \frac{0.25\text{ m}}{\cos 21.8?} = 0.2693\text{ m}$$

Calculate ω_{BD}

$$v_B = (BC)\omega_{BD}$$

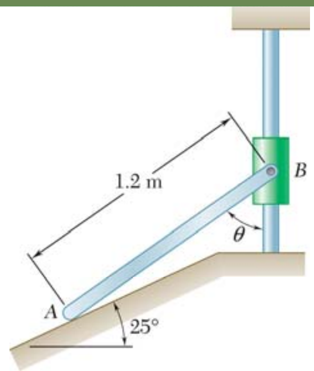
$$1\text{ m/s} = (0.25\text{ m})\omega_{BD}$$

$$\omega_{BD} = 4\text{ rad/s}$$

Find ω_{DE}

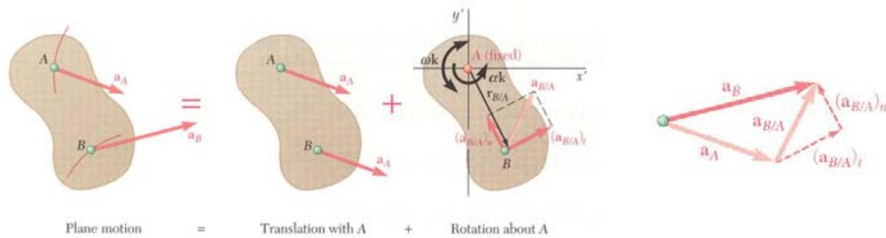
$$v_D = (DC)\omega_{BD} = \frac{0.25\text{ m}}{\cos\beta}(4\text{ rad/s}) \qquad v_D = (DE)\omega_{DE};\quad \frac{1\text{ m/s}}{\cos\beta} = \frac{0.15\text{ m}}{\cos\beta}\omega_{DE};\quad \boxed{\omega_{DE} = 6.67\text{ rad/s}}$$

Problem 15.40



Collar *B* moves upward with a constant velocity of 1.5 m/s. At the instant when θ=50º, determine (a) the angular velocity of rod *AB*, (b) the velocity of end *A* of the rod.

Absolute and Relative Acceleration in Plane Motion



- Absolute acceleration of a particle of the slab,

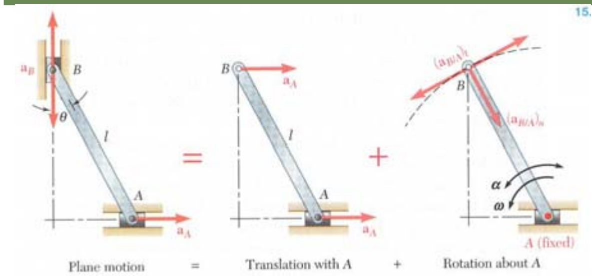
$$\vec{a}_B = \vec{a}_A + \vec{a}_{B/A}$$

- Relative acceleration $\vec{a}_{B/A}$ associated with rotation about *A* includes tangential and normal components,

$$\left(\vec{a}_{B/A}\right)_t = \alpha\vec{k} \times \vec{r}_{B/A} \qquad \left(a_{B/A}\right)_t = r\alpha$$

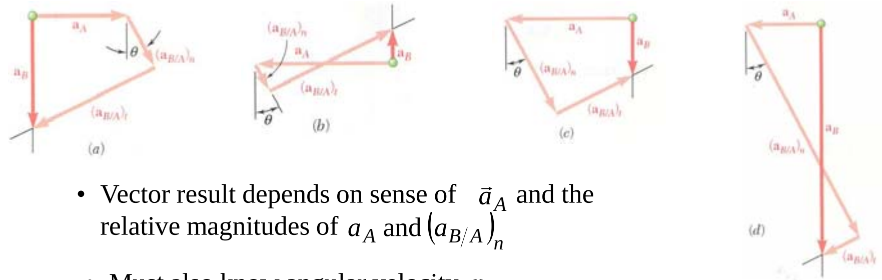
$$\left(\vec{a}_{B/A}\right)_n = -\omega^2 \vec{r}_{B/A} \qquad \left(a_{B/A}\right)_n = r\omega^2$$

Absolute and Relative Acceleration in Plane Motion



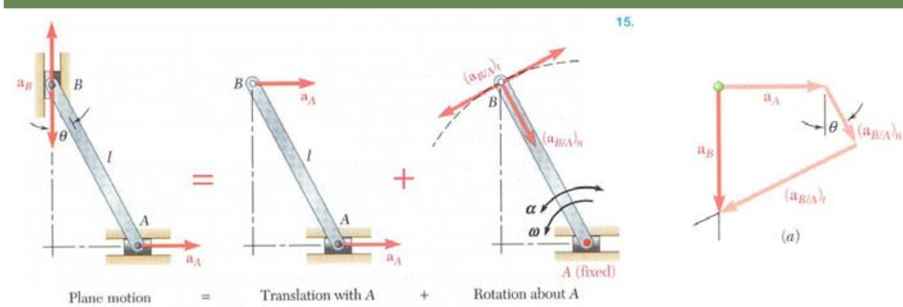
- Given $\vec{a}_A$ and $\vec{v}_A$, determine $\vec{a}_B$ and $\vec{\alpha}$.

$$\vec{a}_B = \vec{a}_A + \vec{a}_{B/A}$$
$$= \vec{a}_A + \left(\vec{a}_{B/A}\right)_n + \left(\vec{a}_{B/A}\right)_t$$



- Vector result depends on sense of $\vec{a}_A$ and the relative magnitudes of a_A and $\left(a_{B/A}\right)_n$
- Must also know angular velocity ω.

Absolute and Relative Acceleration in Plane Motion



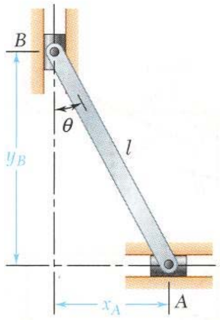
- Write $\vec{a}_B = \vec{a}_A + \vec{a}_{B/A}$ in terms of the two component equations,

$\overset{+}{\rightarrow}$ x components: $0 = a_A + l\omega^2 \sin\theta - l\alpha\cos\theta$

$+\uparrow$ y components: $-a_B = -l\omega^2\cos\theta - l\alpha\sin\theta$

- Solve for a_B and α.

Analysis of Plane Motion in Terms of a Parameter



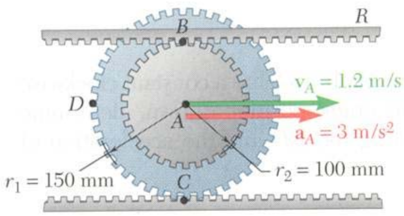
- In some cases, it is advantageous to determine the absolute velocity and acceleration of a mechanism directly.

$$x_A = l\sin\theta \qquad y_B = l\cos\theta$$

$$\begin{aligned} v_A &= \dot{x}_A & v_B &= \dot{y}_B \\ &= l\dot{\theta}\cos\theta & &= -l\dot{\theta}\sin\theta \\ &= l\omega\cos\theta & &= -l\omega\sin\theta \end{aligned}$$

$$\begin{aligned} a_A &= \ddot{x}_A & a_B &= \ddot{y}_B \\ &= -l\dot{\theta}^2\sin\theta + l\ddot{\theta}\cos\theta & &= -l\dot{\theta}^2\cos\theta - l\ddot{\theta}\sin\theta \\ &= -l\omega^2\sin\theta + l\alpha\cos\theta & &= -l\omega^2\cos\theta - l\alpha\sin\theta \end{aligned}$$

Sample Problem 15.6



The center of the double gear has a velocity and acceleration to the right of 1.2 m/s and 3 m/s^2, respectively. The lower rack is stationary.

Determine *(a)* the angular acceleration of the gear, and *(b)* the acceleration of points *B*, *C*, and *D*.

SOLUTION:

- The expression of the gear position as a function of θ is differentiated twice to define the relationship between the translational and angular accelerations.

$$x_A = -r_1\theta$$

$$v_A = -r_1\dot{\theta} = -r_1\omega$$

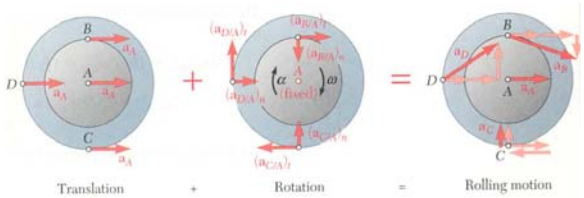
$$\omega = -\frac{v_A}{r_1} = -\frac{1.2\,\mathrm{m/s}}{0.150\,\mathrm{m}} = -8\,\mathrm{rad/s}$$

$$a_A = -r_1\ddot{\theta} = -r_1\alpha$$

$$\alpha = -\frac{a_A}{r_1} = -\frac{3\,\mathrm{m/s^2}}{0.150\,\mathrm{m}}$$

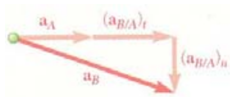
$$\boxed{\vec{\alpha} = \alpha\vec{k} = -\left(20\,\mathrm{rad/s^2}\right)\vec{k}}$$

Sample Problem 15.6



- The acceleration of each point is obtained by adding the acceleration of the gear center and the relative accelerations with respect to the center.

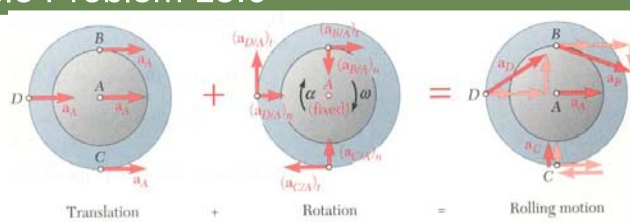
  The latter includes normal and tangential acceleration components.

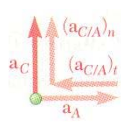


$$
\begin{aligned}
\vec{a}_B &= \vec{a}_A + \vec{a}_{B/A} = \vec{a}_A + \left(\vec{a}_{B/A}\right)_t + \left(\vec{a}_{B/A}\right)_n \\
&= \vec{a}_A + \alpha\vec{k} \times \vec{r}_{B/A} - \omega^2 \vec{r}_{B/A} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} - \left(20\,\mathrm{rad/s^2}\right)\vec{k} \times (0.100\,\mathrm{m})\vec{j} - (8\,\mathrm{rad/s})^2(-0.100\,\mathrm{m})\vec{j} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} + \left(2\,\mathrm{m/s^2}\right)\vec{i} - \left(6.40\,\mathrm{m/s^2}\right)\vec{j}
\end{aligned}
$$

$$\boxed{\vec{a}_B = \left(5\,\mathrm{m/s^2}\right)\vec{i} - \left(6.40\,\mathrm{m/s^2}\right)\vec{j} \qquad a_B = 8.12\,\mathrm{m/s^2}}$$

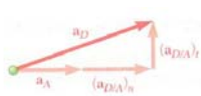
Sample Problem 15.6





$$
\begin{aligned}
\vec{a}_C &= \vec{a}_A + \vec{a}_{C/A} = \vec{a}_A + \alpha\vec{k} \times \vec{r}_{C/A} - \omega^2 \vec{r}_{C/A} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} - \left(20\,\mathrm{rad/s^2}\right)\vec{k} \times (-0.150\,\mathrm{m})\vec{j} - (8\,\mathrm{rad/s})^2(-0.150\,\mathrm{m})\vec{j} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} - \left(3\,\mathrm{m/s^2}\right)\vec{i} + \left(9.60\,\mathrm{m/s^2}\right)\vec{j}
\end{aligned}
$$

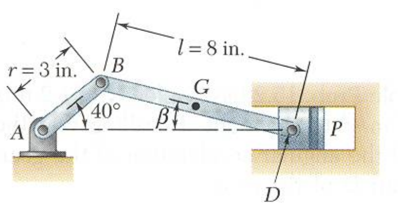
$$\boxed{\vec{a}_c = \left(9.60\,\mathrm{m/s^2}\right)\vec{j}}$$



$$
\begin{aligned}
\vec{a}_D &= \vec{a}_A + \vec{a}_{D/A} = \vec{a}_A + \alpha\vec{k} \times \vec{r}_{D/A} - \omega^2 \vec{r}_{D/A} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} - \left(20\,\mathrm{rad/s^2}\right)\vec{k} \times (-0.150\,\mathrm{m})\vec{i} - (8\,\mathrm{rad/s})^2(-0.150\mathrm{m})\vec{i} \\
&= \left(3\,\mathrm{m/s^2}\right)\vec{i} + \left(3\,\mathrm{m/s^2}\right)\vec{j} + \left(9.60\,\mathrm{m/s^2}\right)\vec{i}
\end{aligned}
$$

$$\boxed{\vec{a}_D = \left(12.6\,\mathrm{m/s^2}\right)\vec{i} + \left(3\,\mathrm{m/s^2}\right)\vec{j} \qquad a_D = 12.95\,\mathrm{m/s^2}}$$

Sample Problem 15.7



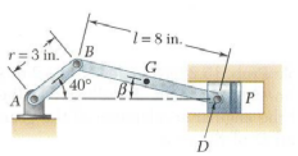
Crank *AG* of the engine system has a constant clockwise angular velocity of 2000 rpm.

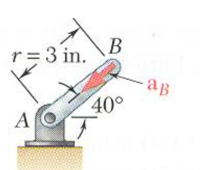
For the crank position shown, determine the angular acceleration of the connecting rod *BD* and the acceleration of point *D*.

SOLUTION:

- The angular acceleration of the connecting rod *BD* and the acceleration of point *D* will be determined from
  $\vec{a}_D = \vec{a}_B + \vec{a}_{D/B} = \vec{a}_B + \left(\vec{a}_{D/B}\right)_t + \left(\vec{a}_{D/B}\right)_n$
- The acceleration of *B* is determined from the given rotation speed of *AB*.
- The directions of the accelerations $\vec{a}_D$, $\left(\vec{a}_{D/B}\right)_t$, and $\left(\vec{a}_{D/B}\right)_n$ are determined from the geometry.
- Component equations for acceleration of point *D* are solved simultaneously for acceleration of *D* and angular acceleration of the connecting rod.

Sample Problem 15.7



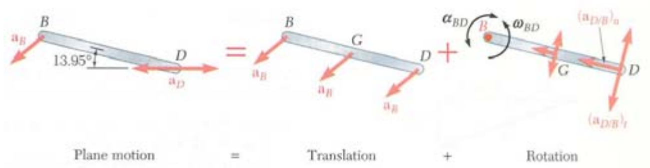


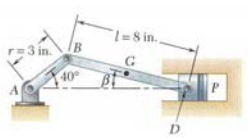
SOLUTION:

- The angular acceleration of the connecting rod *BD* and the acceleration of point *D* will be determined from
  $$\vec{a}_D = \vec{a}_B + \vec{a}_{D/B} = \vec{a}_B + \left(\vec{a}_{D/B}\right)_t + \left(\vec{a}_{D/B}\right)_n$$
- The acceleration of *B* is determined from the given rotation speed of *AB*.

$$\omega_{AB} = 2000\,\text{rpm} = 209.4\,\text{rad/s} = \text{constant}$$
$$\alpha_{AB} = 0$$
$$a_B = r\omega_{AB}^2 = \left(\tfrac{3}{12}\,\text{ft}\right)\left(209.4\,\text{rad/s}\right)^2 = 10{,}962\,\text{ft/s}^2$$
$$\vec{a}_B = \left(10{,}962\,\text{ft/s}^2\right)\left(-\cos 40°\,\vec{i} - \sin 40°\,\vec{j}\right)$$

Sample Problem 15.7





- The directions of the accelerations $\vec{a}_D$, $\left(\vec{a}_{D/B}\right)_t$, and $\left(\vec{a}_{D/B}\right)_n$ are determined from the geometry.

$$\vec{a}_D = \mp a_D \vec{i}$$

From Sample Problem 15.3, $\omega_{BD} = 62.0$ rad/s, $\beta = 13.95°$.

$$\left(a_{D/B}\right)_n = (BD)\omega_{BD}^2 = \left(\tfrac{8}{12}\text{ ft}\right)(62.0\,\text{rad/s})^2 = 2563\,\text{ft/s}^2$$

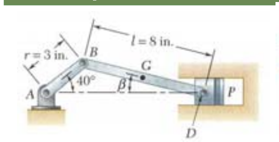
$$\left(\vec{a}_{D/B}\right)_n = \left(2563\,\text{ft/s}^2\right)\left(-\cos 13.95°\vec{i} + \sin 13.95°\vec{j}\right)$$

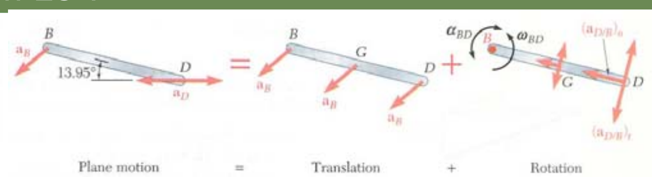
$$\left(a_{D/B}\right)_t = (BD)\alpha_{BD} = \left(\tfrac{8}{12}\text{ ft}\right)\alpha_{BD} = 0.667\alpha_{BD}$$

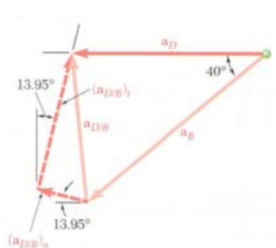
The direction of $(a_{D/B})_t$ is known but the sense is not known,

$$\left(\vec{a}_{D/B}\right)_t = \left(0.667\alpha_{BD}\right)\left(\pm\sin 76.05°\vec{i} \pm \cos 76.05°\vec{j}\right)$$

Sample Problem 15.7







- Component equations for acceleration of point D are solved simultaneously.

$$\vec{a}_D = \vec{a}_B + \vec{a}_{D/B} = \vec{a}_B + \left(\vec{a}_{D/B}\right)_t + \left(\vec{a}_{D/B}\right)_n$$

x components:

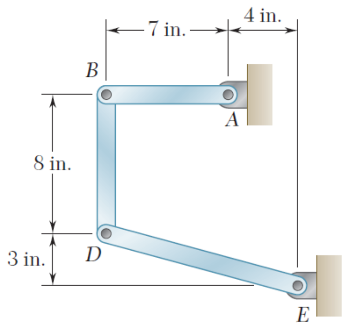
$$-a_D = -10{,}962\cos 40° - 2563\cos 13.95° + 0.667\alpha_{BD}\sin 13.95°$$

y components:

$$0 = -10{,}962\sin 40° + 2563\sin 13.95° + 0.667\alpha_{BD}\cos 13.95°$$

$$\boxed{\begin{aligned}\vec{\alpha}_{BD} &= \left(9940\,\text{rad/s}^2\right)\vec{k}\\ \vec{a}_D &= -\left(9290\,\text{ft/s}^2\right)\vec{i}\end{aligned}}$$

Example



Knowing that at the instant shown bar *AB* has a constant angular velocity of 4 rad/s clockwise, determine the angular acceleration of bars *BD* and *DE*.

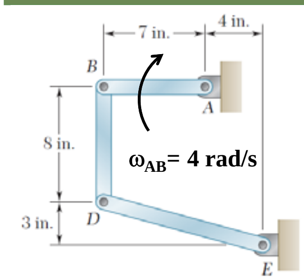
SOLUTION:

- The angular velocities were determined in a previous problem by simultaneously solving the component equations for

$$\vec{v}_D = \vec{v}_B + \vec{v}_{D/B}$$

- The angular accelerations are now determined by simultaneously solving the component equations for the relative acceleration equation.

Example



From our previous problem, we used the relative velocity equations to find that:

$$\omega_{DE} = 2.55 \text{ rad/s} \qquad \omega_{BD} = 0.955 \text{ rad/s}$$

We can now apply the relative acceleration equation with $\alpha_{AB} = 0$

Analyze Bar AB

$$\mathbf{a}_B = \cancel{\mathbf{a}}_A + \cancel{\boldsymbol{\alpha}}_{AB} \times \mathbf{r}_{B/A} - \omega_{AB}^2 \mathbf{r}_{B/A}$$

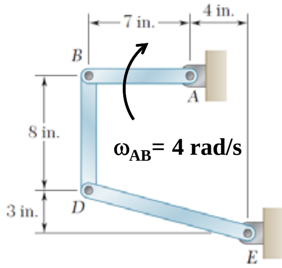
$$\mathbf{a}_B = -\omega_{AB}^2 \mathbf{r}_{B/A} = -(4)^2(-7\mathbf{i}) = 112 \text{ in./s}^2\mathbf{i}$$

Analyze Bar BD

$$\mathbf{a}_D = \mathbf{a}_B + \boldsymbol{\alpha}_{BD} \times \mathbf{r}_{D/B} - \omega_{BD}^2 \mathbf{r}_{D/B} = 112\mathbf{i} + \alpha_{BD}\mathbf{k} \times (-8\mathbf{j}) - (0.95455)^2(-8\mathbf{j})$$

$$\mathbf{a}_D = (112 + 8\,\alpha_{BD})\mathbf{i} + 7.289\,\mathbf{j}$$

Example



Analyze Bar DE

$$\mathbf{a}_D = \boldsymbol{\alpha}_{DE} \times \mathbf{r}_{D/E} - \omega_{DE}^2 r_{D/E}$$
$$= \alpha_{DE}\mathbf{k} \times (-11\mathbf{i} + 3\mathbf{j}) - (2.5455)^2(-11\mathbf{i} + 3\mathbf{j})$$
$$= -11\alpha_{DE}\mathbf{j} - 3\alpha_{DE}\mathbf{i} + 71.275\mathbf{i} - 19.439\mathbf{j}$$

$$\mathbf{a}_D = (-3\alpha_{DE} + 71.275)\mathbf{i} - (11\alpha_{DE} + 19.439)\mathbf{j}$$

From previous page, we had: $\mathbf{a}_D = (112 + 8\,\alpha_{BD})\mathbf{i} + 7.289\mathbf{j}$

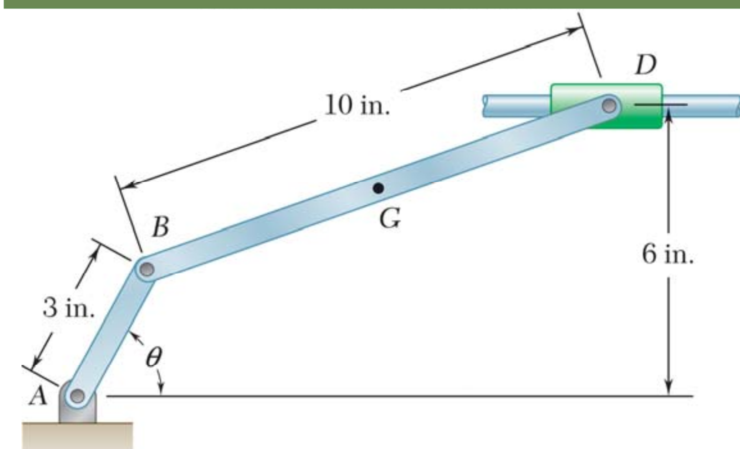
Equate like components of $\mathbf{a}_D$

j: $7.289 = -(11\alpha_{DE} + 19.439)$

i: $112 + 8\alpha_{BD} = [-(3)(-2.4298) + 71.275]$

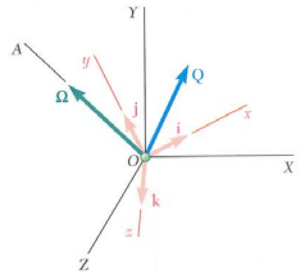
$$\boxed{\alpha_{DE} = -2.4298 \text{ rad/s}^2 \qquad \alpha_{BD} = -4.1795 \text{ rad/s}^2}$$

Problem 15.124



Arm *AB* has a constant angular velocity of 16 rad/s counterclockwise. At the instant when θ=90º, determine the acceleration (a) of collar *D*, (b) of the midpoint *G* of bar *BD*.

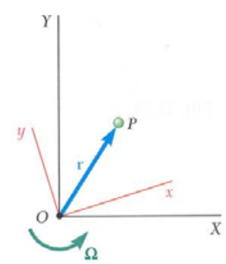
Rate of Change With Respect to a Rotating Frame

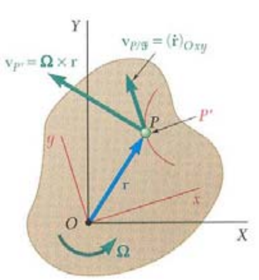


- Frame *OXYZ* is fixed.
- Frame *Oxyz* rotates about fixed axis *OA* with angular velocity $\vec{\Omega}$
- Vector function $\vec{Q}(t)$ varies in direction and magnitude.

- With respect to the rotating *Oxyz* frame,
$$\vec{Q} = Q_x\vec{i} + Q_y\vec{j} + Q_z\vec{k}$$
$$\left(\dot{\vec{Q}}\right)_{Oxyz} = \dot{Q}_x\vec{i} + \dot{Q}_y\vec{j} + \dot{Q}_z\vec{k}$$
- With respect to the fixed *OXYZ* frame,
$$\left(\dot{\vec{Q}}\right)_{OXYZ} = \dot{Q}_x\vec{i} + \dot{Q}_y\vec{j} + \dot{Q}_z\vec{k} + Q_x\dot{\vec{i}} + Q_y\dot{\vec{j}} + Q_z\dot{\vec{k}}$$
- $\dot{Q}_x\vec{i} + \dot{Q}_y\vec{j} + \dot{Q}_z\vec{k} = \left(\dot{\vec{Q}}\right)_{Oxyz}$ = rate of change with respect to rotating frame.
- If $\vec{Q}$ were fixed within *Oxyz* then $\left(\dot{\vec{Q}}\right)_{OXYZ}$ is equivalent to velocity of a point in a rigid body attached to *Oxyz* and $Q_x\dot{\vec{i}} + Q_y\dot{\vec{j}} + Q_z\dot{\vec{k}} = \vec{\Omega}\times\vec{Q}$
- With respect to the fixed *OXYZ* frame,
$$\left(\dot{\vec{Q}}\right)_{OXYZ} = \left(\dot{\vec{Q}}\right)_{Oxyz} + \vec{\Omega}\times\vec{Q}$$

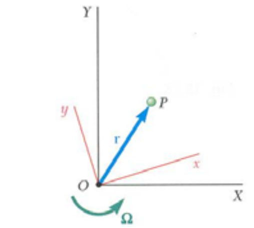
Coriolis Acceleration



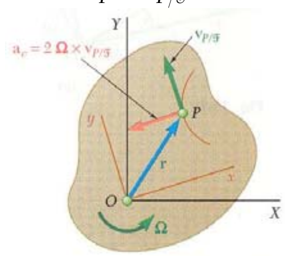


- Frame *OXY* is fixed and frame *Oxy* rotates with angular velocity $\vec{\Omega}$.
- Position vector $\vec{r}_P$ for the particle *P* is the same in both frames but the rate of change depends on the choice of frame.
- The absolute velocity of the particle *P* is
$$\vec{v}_P = \left(\dot{\vec{r}}\right)_{OXY} = \vec{\Omega}\times\vec{r} + (\dot{r})_{Oxy}$$
- Imagine a rigid slab attached to the rotating frame *Oxy* or $\mathfrak{F}$ for short. Let *P'* be a point on the slab which corresponds instantaneously to position of particle *P*.
$\vec{v}_{P/\mathfrak{F}} = \left(\dot{\vec{r}}\right)_{Oxy}$ = velocity of *P* along its path on the slab
$\vec{v}_{P'}$ = absolute velocity of point *P'* on the slab
- Absolute velocity for the particle P may be written as
$$\vec{v}_P = \vec{v}_{P'} + \vec{v}_{P/\mathfrak{F}}$$

Coriolis Acceleration

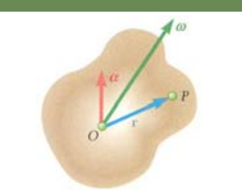


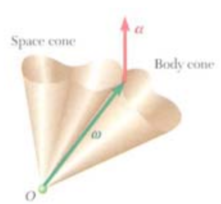
$$\vec{v}_P = \vec{\Omega} \times \vec{r} + (\dot{r})_{Oxy}$$
$$= \vec{v}_{P'} + \vec{v}_{P/\mathcal{F}}$$

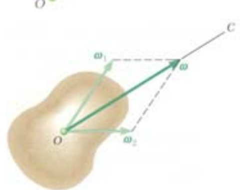


- Absolute acceleration for the particle P is
$$\vec{a}_P = \dot{\vec{\Omega}} \times \vec{r} + \vec{\Omega} \times (\dot{\vec{r}})_{OXY} + \frac{d}{dt}\left[(\dot{\vec{r}})_{Oxy}\right]$$
but, $\quad (\dot{\vec{r}})_{OXY} = \vec{\Omega} \times \vec{r} + (\dot{\vec{r}})_{Oxy}$
$$\frac{d}{dt}\left[(\dot{\vec{r}})_{Oxy}\right] = (\ddot{\vec{r}})_{Oxy} + \vec{\Omega} \times (\dot{\vec{r}})_{Oxy}$$
$$\vec{a}_P = \dot{\vec{\Omega}} \times \vec{r} + \vec{\Omega} \times (\vec{\Omega} \times \vec{r}) + 2\vec{\Omega} \times (\dot{\vec{r}})_{Oxy} + (\ddot{\vec{r}})_{Oxy}$$
- Utilizing the conceptual point P' on the slab,
$$\vec{a}_{P'} = \dot{\vec{\Omega}} \times \vec{r} + \vec{\Omega} \times (\vec{\Omega} \times \vec{r})$$
$$\vec{a}_{P/\mathcal{F}} = (\ddot{\vec{r}})_{Oxy}$$
- Absolute acceleration for the particle P becomes
$$\vec{a}_P = \vec{a}_{P'} + \vec{a}_{P/\mathcal{F}} + 2\vec{\Omega} \times (\dot{\vec{r}})_{Oxy}$$
$$= \vec{a}_{P'} + \vec{a}_{P/\mathcal{F}} + \vec{a}_c$$
$$\vec{a}_c = 2\vec{\Omega} \times (\dot{\vec{r}})_{Oxy} = 2\vec{\Omega} \times \vec{v}_{P/\mathcal{F}} = \text{Coriolis acceleration}$$

Motion About a Fixed Point

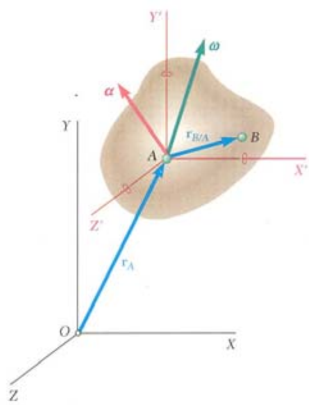






- The most general displacement of a rigid body with a fixed point O is equivalent to a rotation of the body about an axis through O.
- With the instantaneous axis of rotation and angular velocity $\vec{\omega}$, the velocity of a particle P of the body is
$$\vec{v} = \frac{d\vec{r}}{dt} = \vec{\omega} \times \vec{r}$$
and the acceleration of the particle P is
$$\vec{a} = \vec{\alpha} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r}) \qquad \vec{\alpha} = \frac{d\vec{\omega}}{dt}.$$
- The angular acceleration $\vec{\alpha}$ represents the velocity of the tip of $\vec{\omega}$.
- As the vector $\vec{\omega}$ moves within the body and in space, it generates a body cone and space cone which are tangent along the instantaneous axis of rotation.
- Angular velocities have magnitude and direction and obey parallelogram law of addition. They are vectors.

General Motion



- For particles A and B of a rigid body,

  $$\vec{v}_B = \vec{v}_A + \vec{v}_{B/A}$$

- Particle A is fixed within the body and motion of the body relative to $AX'Y'Z'$ is the motion of a body with a fixed point

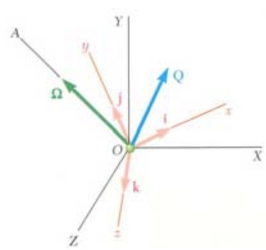
  $$\vec{v}_B = \vec{v}_A + \vec{\omega} \times \vec{r}_{B/A}$$

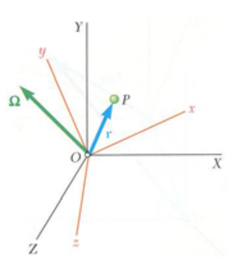
- Similarly, the acceleration of the particle P is

  $$\begin{aligned}\vec{a}_B &= \vec{a}_A + \vec{a}_{B/A} \\ &= \vec{a}_A + \vec{\alpha} \times \vec{r}_{B/A} + \vec{\omega} \times \left(\vec{\omega} \times \vec{r}_{B/A}\right)\end{aligned}$$

- Most general motion of a rigid body is equivalent to:
  - a translation in which all particles have the same velocity and acceleration of a reference particle A, and
  - of a motion in which particle A is assumed fixed.

Three-Dimensional Motion. Coriolis Acceleration





- With respect to the fixed frame $OXYZ$ and rotating frame $Oxyz$,

  $$\left(\dot{\vec{Q}}\right)_{OXYZ} = \left(\dot{\vec{Q}}\right)_{Oxyz} + \vec{\Omega} \times \vec{Q}$$

- Consider motion of particle P relative to a rotating frame $Oxyz$ or $\mathfrak{F}$ for short. The absolute velocity can be expressed as

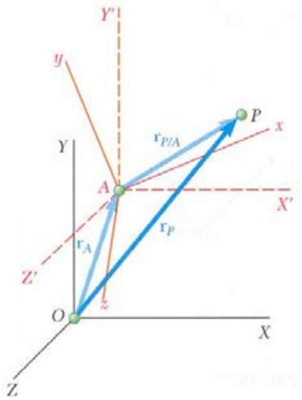
  $$\begin{aligned}\vec{v}_P &= \vec{\Omega} \times \vec{r} + \left(\dot{\vec{r}}\right)_{Oxyz} \\ &= \vec{v}_{P'} + \vec{v}_{P/\mathfrak{F}}\end{aligned}$$

- The absolute acceleration can be expressed as

  $$\begin{aligned}\vec{a}_P &= \dot{\vec{\Omega}} \times \vec{r} + \vec{\Omega} \times \left(\vec{\Omega} \times \vec{r}\right) + 2\vec{\Omega} \times \left(\dot{\vec{r}}\right)_{Oxyz} + \left(\ddot{\vec{r}}\right)_{Oxyz} \\ &= \vec{a}_{p'} + \vec{a}_{P/\mathfrak{F}} + \vec{a}_c\end{aligned}$$

  $$\vec{a}_c = 2\vec{\Omega} \times \left(\dot{\vec{r}}\right)_{Oxyz} = 2\vec{\Omega} \times \vec{v}_{P/\mathfrak{F}} = \text{Coriolis acceleration}$$

Frame of Reference in General Motion



Consider:
- fixed frame *OXYZ*,
- translating frame *AX'Y'Z'*, and
- translating and rotating frame *Axyz* or $\mathfrak{F}$.

- With respect to *OXYZ* and *AX'Y'Z'*,

$$\vec{r}_P = \vec{r}_A + \vec{r}_{P/A}$$
$$\vec{v}_P = \vec{v}_A + \vec{v}_{P/A}$$
$$\vec{a}_P = \vec{a}_A + \vec{a}_{P/A}$$

- The velocity and acceleration of *P* relative to *AX'Y'Z'* can be found in terms of the velocity and acceleration of *P* relative to *Axyz*.

$$\vec{v}_P = \vec{v}_A + \vec{\Omega}\times\vec{r}_{P/A} + \left(\dot{\vec{r}}_{P/A}\right)_{Axyz}$$
$$= \vec{v}_{P'} + \vec{v}_{P/\mathfrak{F}}$$

$$\vec{a}_P = \vec{a}_A + \dot{\vec{\Omega}}\times\vec{r}_{P/A} + \vec{\Omega}\times\left(\vec{\Omega}\times\vec{r}_{P/A}\right) + 2\vec{\Omega}\times\left(\dot{\vec{r}}_{P/A}\right)_{Axyz} + \left(\ddot{\vec{r}}_{P/A}\right)_{Axyz}$$
$$= \vec{a}_{P'} + \vec{a}_{P/\mathfrak{F}} + \vec{a}_c$$