

ME2115 Formulae

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Vector Mechanics

$$\overrightarrow{OB} - \overrightarrow{OA} = \overrightarrow{AB}$$

$$u = |\mathbf{u}| = \sqrt{u_x^2 + u_y^2 + u_z^2}$$

$$\mathbf{u} \cdot \mathbf{v} = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \cdot \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = u_x v_x + u_y v_y + u_z v_z$$

$$\mathbf{u} \times \mathbf{v} = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \times \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} u_y v_z - u_z v_y \\ u_z v_x - u_x v_z \\ u_x v_y - u_y v_x \end{pmatrix}$$

$$\mathbf{u} \times \mathbf{u} = 0$$

$$\mathbf{u} \cdot \mathbf{v} = 0 \text{ (if } \mathbf{u} \perp \mathbf{v} \text{)}$$

$$\mathbf{u} \cdot \mathbf{v} = uv \cos \theta$$

$$\mathbf{u} \times \mathbf{v} = uv \sin \theta \cdot \mathbf{n}$$

Particle Kinematics

Rectilinear Motion

$$dx = v dt \parallel \int_{x_0}^x dx = \int_{t_0}^t v(t) dt$$

$$dv = a dt \parallel \int_v^{v_0} dv = \int_{t_0}^t a(t) dt$$

$$v dv = a dx \parallel \int_{v_0}^v v dv = \int_{x_0}^x a(x) dx$$

Given $a = a(t)$:

$$\int_{v_0}^v dv = \int_{t_0}^t a(t) dt \parallel \int_{x_0}^x dx = \int_{t_0}^t v(t) dt$$

Given $a = a(x)$:

$$\int_{v_0}^v v dv = \int_{x_0}^x a(x) dx \parallel \int_{t_0}^t dt = \int_{x_0}^x \frac{1}{v(x)} dx$$

Given $a = a(v)$:

$$\int_{t_0}^t dt = \int_{v_0}^v \frac{1}{a(v)} dv \parallel \int_{x_0}^x dx = \int_{v_0}^v \frac{v}{a(v)} dv$$

If v is constant:

$$x = x_0 + v(t - t_0)$$

If a is constant:

$$v = v_0 + a(t - t_0)$$

$$x = x_0 + v_0(t - t_0) + \frac{1}{2}a(t - t_0)^2$$

$$v^2 - v_0^2 = 2a(x - x_0)$$

Curvilinear Motion

The previous section can apply to angular motion by replacing x with θ , v with ω , and a with α .

$$s = r\theta$$

$$v_t = r\omega$$

$$a_t = r\alpha$$

$$a_n = \frac{v_t^2}{\rho}$$

Rigid Body Mechanics

General Plane Motion

$$v_B = v_A + v_{B/A}$$

$$\vec{v}_{B/A} = \vec{\omega} \times \vec{r}_{B/A} = v_t$$

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

$$a_{B/A} = \vec{\omega} \times (\vec{\omega} \times \vec{r}_{B/A}) + \vec{\alpha} \times \vec{r}_{B/A} = \vec{a}_n + \vec{a}_t$$

Rolling without Sliding

* velocity at contact point always 0

$$v_o = r\omega$$

$$a_t = r\alpha$$

$$\vec{a}_c = \vec{\alpha} \times \vec{r}_{c/o}$$

$$\vec{v}_c = \vec{\omega} \times \vec{r}_{c/o}$$

Mass Properties

$$dW = \gamma t dA \equiv W = \gamma t A$$

$$\bar{x}A = \int x dA = Q_y$$

$$\bar{y}A = \int y dA = Q_x$$

Compound Shapes

$$Q_y = \bar{X} \sum A = \sum \bar{x}A$$

$$Q_y = \bar{Y} \sum A = \sum \bar{y}A$$

Mass Moment of Inertia

$$I_O = \int r^2 dm = mk_o^2$$

$$I = I_O + md^2$$

Rigid Body Kinetics

$$\Sigma F = m\bar{a} = \Sigma F_{eff}.$$

$$\Sigma M_G = \bar{I}\alpha = \Sigma M_{eff}.$$

More generally,

$$\Sigma M_i + \Sigma (\vec{r}_{i/A} \times \vec{F}_i) = M_A = I_G \vec{\alpha} + \vec{r}_{G/A} \times m \vec{a}_G$$

$$M_A = (I_G + mr_{G/A}^2) \vec{\alpha} = I_A \vec{\alpha}$$

$$\bar{a} = a_{ref} + r\omega^2 e_n + r\alpha e_t$$

Principle of Work and Energy

$$U_{1 \rightarrow 2} = \int \vec{F} d\vec{r} + \int M d\theta = T_2 - T_1$$

$$T_i = \frac{1}{2} m |\vec{v}_i|^2 + \frac{1}{2} I_G \omega^2$$

Work of Conservative Forces

$$U_{1 \rightarrow 2} = U_2 - U_1 = V_1 - V_2$$

$$V_1 + T_1 = V_2 + T_2$$

Free Vibration Without Damping

$$\ddot{u} + \omega_n^2 u = 0$$

$$\omega_n = \sqrt{\frac{k}{m}}$$

Natural Parameters

$$\tau_n = \frac{2\pi}{\omega_n}$$

$$f_n = \frac{\omega_n}{2\pi} \text{ (in Hz)}$$

General Solution

$$u = A \sin(\omega_n t + \phi)$$

$$A = \sqrt{x_o^2 + \left(\frac{v_o}{\omega_n}\right)^2}$$

$$\phi = \tan^{-1}\left(\frac{x_o \omega_n}{v_o}\right)$$

Pendulum

$$\ddot{\theta} + \frac{g}{l} \theta = 0$$

$$\omega_n = \sqrt{\frac{g}{l}}$$

Generic Rigid Body

$$\omega_n = \sqrt{\frac{mgd}{I_O}}$$

Free Vibration with Damping

Spring-Mass-Damper System

$$m\ddot{x} + c\dot{x} + kx = 0$$

$$\lambda = -\frac{c}{2m} \pm \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$

Overdamped ($((\frac{c}{2m})^2 - \frac{k}{m}) > 0$)

$$x = A_1 e^{\lambda_1 t} + A_2 e^{\lambda_2 t}$$

Critically Damped ($((\frac{c}{2m})^2 - \frac{k}{m}) = 0$)

$$c_{cr} = 2\sqrt{mk} = 2m\omega_n$$

$$x = (A_1 + A_2 t) e^{-\omega_n t}$$

Underdamped ($((\frac{c}{2m})^2 - \frac{k}{m}) < 0$)

Equation of Motion

$$\ddot{x} + 2\zeta\omega_n \dot{x} + \omega_n^2 x = 0$$

$$x = X e^{-\zeta\omega_n t} \sin(\omega_d t + \phi)$$

Exponential Decay Coefficient

$$\alpha = \frac{c}{2m} = \zeta\omega_n$$

Damped Oscillation Frequency

$$\omega_d = \sqrt{\frac{k}{m} - \left(\frac{c}{2m}\right)^2} = \omega_n \sqrt{1 - \zeta^2}$$

Damping Ratio

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2\sqrt{km}}$$

Initial Conditions

$$X = \sqrt{C_1^2 + C_2^2} = \sqrt{\left(\frac{v_o + \zeta\omega_n x_o}{\omega_d}\right)^2 + x_o^2}$$

$$\phi = \tan^{-1}\left(\frac{C_1}{C_2}\right) = \tan^{-1}\left(\frac{\omega_d x_o}{v_o + \zeta\omega_n x_o}\right)$$

Logarithmic Decrement

$$\delta = \ln\left(\frac{x_1}{x_2}\right) = \zeta\omega_n \tau_d$$

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}}$$

$$\delta = \frac{1}{N} \ln\left(\frac{x_1}{x_{1+N}}\right)$$

Tips

- Rigid Body EFDs can be placed on every member in a Rigid Body (use relative acceleration/velocity to find direction of movement)
- Only tangential movement with fixed rotation (hinges, links)
- Movement of an item attached to a pulley = movement of the point of attachment (displacement, acceleration, velocity)
- For **Constrained Motion** - do kinematic analysis (relative velocity/acceleration) then kinetic analysis (equate FBD to EFD)
- Use moments about points that eliminate as many forces as possible
- **Law of Sines:** $\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$ for any triangle

	\bar{x}	\bar{y}	Area
		$\frac{h}{3}$	$\frac{bh}{2}$
	$\frac{4r}{3\pi}$	$\frac{4r}{3\pi}$	$\frac{\pi r^2}{4}$
	0	$\frac{4r}{3\pi}$	$\frac{\pi r^2}{2}$
	$\frac{4a}{3\pi}$	$\frac{4b}{3\pi}$	$\frac{\pi ab}{4}$
	0	$\frac{4b}{3\pi}$	$\frac{\pi ab}{2}$
	$\frac{3a}{8}$	$\frac{3h}{5}$	$\frac{2ah}{3}$
	0	$\frac{3h}{5}$	$\frac{4ah}{3}$
	$\frac{3a}{4}$	$\frac{3h}{10}$	$\frac{ah}{3}$
	$\frac{n+1}{n+2} a$	$\frac{n+1}{4n+2} h$	$\frac{ah}{n+1}$
	$\frac{2r \sin \alpha}{3\alpha}$	0	αr^2

Number of Unknowns	1	1	1	2	3
Reaction					
Support or Connection	Frictionless surface Rocker Rollers	Short link Short cable	Frictionless pin in slot Collar on frictionless rod	Rough surface Frictionless pin or hinge	Fixed support

Slender rod		$I_y = I_z = \frac{1}{12} mL^2$
Thin rectangular plate		$I_x = \frac{1}{12} m(b^2 + c^2)$ $I_y = \frac{1}{12} mc^2$ $I_z = \frac{1}{12} mb^2$
Rectangular prism		$I_x = \frac{1}{12} m(b^2 + c^2)$ $I_y = \frac{1}{12} m(c^2 + a^2)$ $I_z = \frac{1}{12} m(a^2 + b^2)$
Thin disk		$I_x = \frac{1}{2} mr^2$ $I_y = I_z = \frac{1}{4} mr^2$
Circular cylinder		$I_x = \frac{1}{2} ma^2$ $I_y = I_z = \frac{1}{12} m(3a^2 + L^2)$
Circular cone		$I_x = \frac{3}{10} ma^2$ $I_y = I_z = \frac{3}{5} m(\frac{1}{4} a^2 + h^2)$
Sphere		$I_x = I_y = I_z = \frac{2}{5} ma^2$
Semicircular disk		$I_x = \frac{1}{2} mr^2$ $I_y = I_z = \frac{1}{4} mr^2$

Thick-walled hollow sphere		$I = \frac{2m}{5} \left(\frac{r_2^5 - r_1^5}{r_2^3 - r_1^3} \right)$
Thick-walled hollow cylinder		$I_x = I_y = \frac{1}{12} m \left[\frac{r_2^4 - r_1^4}{r_2^2 - r_1^2} + h^2 \right]$
Solid sphere		$I = \frac{2}{5} mr^2$
Solid cylinder		$I_z = \frac{1}{2} mr^2$
Hollow sphere		$I = \frac{2}{3} mr^2$
Thin-walled hollow cylinder		$I = mr^2$