

# Answers to Odd Problems in Intermediate Dynamics

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## Chapter 1

- 1.1 75.17 cm/sec at  $3.81^\circ$  above the horizontal  
1.3 (a)  $1.44 ft/sec^2$ , (b) 102.3 mph.  
1.5  $v = \frac{k}{b^2} [1 - e^{-bt}(bt + 1)]$ ,  $x = x_0 + \frac{k}{b^2} [e^{-bt} (t + \frac{2}{b}) + t - \frac{2}{b}]$   
1.7  $t = 0.1$  sec.  
1.11 5609 m.  
1.13 15.7 m  
1.15 0.21  
1.19 (a)  $(\frac{4a}{3\pi}, \frac{4b}{3\pi})$ . (b)  $x_{cm} = 0, y_{cm} = \frac{4}{3\pi} \frac{b^3 - a^3}{b^2 - a^2}$ , (c) (16.77, 8).  
1.21  $R_{cm} = (\frac{3}{8}R, \frac{3}{8}R, \frac{3}{8}R)$ .  
1.23  $\frac{3\sqrt{2}}{16}a$ .  
1.25  $21.37^\circ$   
1.27  $5mg$ .  
1.29 (a) 1.7 mph (b) 2.4 mph.  
1.31 3520 watt.  
1.33 4.3 m/s.  
1.35  $v_i/v_f = 0.89$ ; the streetcars will run about 10 percent faster.

## Chapter 2

- 2.1 6 m/s.  
2.3 (a)  $v = \frac{v_0}{1 + kv_0 t}$ ,  $x = x_0 + \frac{1}{k} [\ln(1 + kv_0 t)]$  (b) As  $t \rightarrow \infty$ ,  $v \rightarrow 0$ .  
2.5  $v = \sqrt{v_{0x}^2 + v_{0y}^2} = [(g^2 x^2 / 2yg) + (2yg)]^{1/2}$ ,  
 $\theta = \tan^{-1}(v_{0y}/v_{0x}) = \tan^{-1}(2y/x)$ .  
2.7 455 km.  
2.9 (a)  $\tau = 2\pi\sqrt{\frac{r}{a}}$  (b)  $a = 9.81$  m/s,  $v = 7.91 \times 10^3$  m/s,  $\tau = 84.4$  min.  
2.11  $\Delta\tau/\tau = \frac{3}{2} (\Delta r/r)$ .  
2.19  $\mathbf{v} = 4 \sin \theta \hat{\mathbf{r}} + (4 - 4 \cos \theta) \hat{\boldsymbol{\theta}}$ ,  $\mathbf{a} = (32 \cos \theta - 16)\hat{\mathbf{r}} + 32 \sin \theta \hat{\boldsymbol{\theta}}$ .

- 2.21  $\hat{\mathbf{r}}(\ddot{r} - 3\dot{r}\dot{\theta}^2 - 3r\ddot{\theta}) + \hat{\boldsymbol{\theta}}(r\ddot{\theta} + 3\dot{r}\ddot{\theta} + 3\dot{r}\dot{\theta} - r\dot{\theta}^3)$ .  
 2.25 0.996 m/s.  
 2.27  $2 + \frac{1}{\rho}z \cos \phi + \frac{1}{2}\sqrt{\frac{\rho}{z}}$ .  
 2.29  $x = a \cos \omega(t - \tau_1) \cos \Omega(t - \tau_2)$ ,  
 $y = -a \cos \omega(t - \tau_1) \sin \Omega(t - \tau_2)$ ,  
 $z = a \sin \omega(t - \tau_1)$ .  
 2.31  $r^2 = \rho^2 + z^2, \theta = \tan^{-1} \frac{\rho}{z}, \phi = \phi; \rho = r \sin \theta, \phi = \phi, z = r \cos \theta$ .  
 2.33 (a) An inward spiral. (b)  $\sqrt{b^2 + (akt - bkt^2)^2}$ .

### Chapter 3

- 3.1  $-\omega A \sin \omega t, -\omega^2 A \cos \omega t$ .  
 3.3  $8 \times 10^4$  N.  
 3.5  $\frac{M_2}{M_1}, \frac{M_2}{M_1}$ .  
 3.7 (a)  $a = -g \frac{m_1 - m_2}{m_1 + m_2}, T = 2 \frac{m_1 m_2}{m_1 + m_2} g$  (b)  $g(m_1 - m_2)/(m_1 + m_2 - I/R^2)$ .  
 3.11  $T/T_0 = (7 \times 10^6)^{0.001/2} = 1.0079$ . Periods differ by about 0.8%; could be detected easily.  
 3.13 (a) (1)Book/Earth (gravitational); Book/Table (electrostatic); Table/Surface (electrostatic); Table/Earth(gravitational) (2)Rocket/Earth (gravitational); Rocket/Plume (molecular collisions - fundamentally electrostatic), Plume/Atmosphere (molecular collisions) (3) Donkey/Road (friction); Donkey/Cart (mechanical). (b) Unbalanced force on inner wall opposite to nozzle. (c) Road on donkey's hooves.  
 3.15  $5L/6, 5L/6$ .  
 3.17 (a)  $v = \frac{F}{m_0} \frac{t}{1 - (\kappa t/m_0)}, x = \frac{F m_0}{\kappa^2} \left[ -\frac{\kappa}{m_0} t - \ln(1 - \frac{\kappa}{m_0} t) \right]$ ,  
 (b)  $\frac{1}{2} \frac{F}{m_0} t^2 + \dots$   
 3.19  $T_{bot} = 2156$  N;  $T_{mid} = 2207$  N;  $T_{top} = 2259$  N;  
 Equation:  $T(x) = g(220 + 7x)$ .  
 3.21 358 m/s.  
 3.25 32.67 m/s, 77.33 m.  
 3.27  $v(t) = -\frac{1}{b} \ln \left( e^{-bv_0} + \frac{A}{bm} t \right)$   
 3.29  $v(t) = \sqrt{mg/b} \tanh \sqrt{gb/mt}$ ,  
 $x(t) = \frac{m}{b} \log \cosh \sqrt{gb/mt} = \frac{m}{b} \log \frac{e^{\sqrt{gb/mt}} + e^{-\sqrt{gb/mt}}}{2}$ .  
 3.31 (a)  $v_T = \sqrt{mg/D}$ ,  
 (b)  $h = (m/2D) \ln [(v_0^2 + v_T^2)/v_T^2]$ ,  
 (c)  $v_g = v_T v_0 / \sqrt{v_0^2 + v_T^2}$ .  
 3.33 (a) 21.8 m<sup>2</sup>, (b) 0.35 s.  
 3.35 (a) 55.87 m/s.  
 (b)  $v = v_T \sqrt{1 - \exp(-2gx/v_T^2)}$ .  
 (c) 38.2 m/s.  
 3.37  $y = \frac{mg}{b} \left( t + \frac{m}{b} (e^{-bt/m} - 1) \right)$ .  
 3.39 (a) 90 m/s, (b) 14.7 s.  
 3.41 1.67 m/s.  
 3.43  $\sqrt{x_0^3 \pi^2 / 8GM}$ .

$$3.45 \quad (\text{a}) x(t) = \frac{D}{2} e^{\sqrt{\beta}t} + \left(\frac{C^2}{2D}\right) e^{-\sqrt{\beta}t}.$$

$$(\text{b}) v_0 = -\sqrt{\frac{k}{m}} x_0.$$

$$3.47 \quad 1.26 \times 10^3 \text{ s} \simeq 42 \text{ min.}$$

#### Chapter 4

$$4.1 \quad L = \frac{1}{2} m a^2 \dot{\theta}^2 + \frac{1}{2} m a^2 \dot{\phi}^2 \sin^2 \theta - m g a \cos \theta.$$

$$4.3 \quad L = \frac{1}{2} m \dot{z}^2 - \frac{3}{2} k z^2 - 3C.$$

$$4.5 \quad \text{Equations of motion: } (M+m)\ddot{x} + Ml\ddot{\theta} \cos \theta - Ml\dot{\theta}^2 \sin \theta = 0 \\ Ml^2\ddot{\theta} + Ml\ddot{x} \cos \theta + mgl \sin \theta = 0.$$

$$\text{Constant of the motion: } (M+m)\dot{x} + Ml\dot{\theta} \cos \theta.$$

$$4.7 \quad \ddot{s} = \frac{g \sin \alpha}{1 - [m/(m+M)] \cos^2 \alpha} \text{ and } \ddot{X} = -\frac{m}{m+M} \left( \frac{g \sin \alpha}{1 - [m/(m+M)] \cos^2 \alpha} \right) \cos \alpha.$$

$$4.9 \quad L = \left(\frac{1}{2}M + 3m\right) \dot{s}^2 + (M + 4m)gs \sin \alpha.$$

$$4.11 \quad (\text{a}) L = \frac{1}{2}(M+m)\dot{X}^2 + m\dot{X}\dot{s} \cos \alpha + \frac{1}{2}m\dot{s}^2 + mgs \sin \alpha - \frac{1}{2}ks^2.$$

$$(\text{b}) p_X = (m+M)\dot{X} + m\dot{s} \cos \alpha, p_s = m\dot{X} \cos \alpha + m\dot{s}.$$

$$(\text{c}) (m+M)\ddot{X} + m\ddot{s} \cos \alpha = 0, m\dot{X} \cos \alpha + m\dot{s} - mg \sin \alpha + ks = 0.$$

$$4.13 \quad (\text{a}) L = m\dot{x}^2 + mg(l-x) - \frac{1}{2}k(d-x)^2.$$

$$(\text{b}) 2m\ddot{x} + kx = kd - mg \text{ or } \frac{2m}{k}\ddot{x} = -x - C.$$

$$(\text{c}) \sqrt{k/2m}.$$

$$4.15 \quad a\sqrt{1 + \phi'^2 \sin^2 \theta}.$$

$$4.17 \quad y = \pm 2c\sqrt{x - c^2} + d.$$

$$4.19 \quad \Phi = y\sqrt{1 + y'^2}.$$

$$4.21 \quad -\frac{\hbar^2}{2m} \left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right].$$

$$4.23 \quad H = \frac{p_\theta^2}{2ml^2} - mgl \cos \theta, \dot{p}_\theta = -mgl \sin \theta, \dot{\theta} = \frac{p_\theta}{ml^2}.$$

#### Chapter 5

$$5.1 \quad 49.5 \text{ J.}$$

$$5.3 \quad 2kR^2.$$

$$5.5 \quad (\text{a}) h_{11}^2 = 1 \quad h_{22}^2 = r^2 \quad h_{12}^2 = 0 \quad h_{21}^2 = 0$$

$$(\text{b}) ds = \hat{\mathbf{r}}dr + \hat{\boldsymbol{\theta}}rd\theta, da = r dr d\theta.$$

$$5.7 \quad \begin{pmatrix} a(\sinh^2 u \cos^2 v + \cosh^2 u \sin^2 v)^{1/2} & 0 & 0 \\ 0 & a(\cosh^2 u \sin^2 v + \sinh^2 u \cos^2 v)^{1/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$ds = a(\sinh^2 u \cos^2 v + \cosh^2 u \sin^2 v)^{1/2} du \hat{\mathbf{e}}_u \\ + a(\cosh^2 u \sin^2 v + \sinh^2 u \cos^2 v)^{1/2} dv \hat{\mathbf{e}}_v + dz \hat{\mathbf{k}}.$$

$$5.9 \quad \nabla = \hat{\mathbf{e}}_\eta \left( 1/a [\cosh^2 \eta \sin^2 \theta + \sinh^2 \eta \cos^2 \theta]^{1/2} \right) \frac{\partial}{\partial \eta} \\ + \hat{\mathbf{e}}_\theta \left( 1/a [\sinh^2 \eta \cos^2 \theta + \cosh^2 \eta \sin^2 \theta]^{1/2} \right) \frac{\partial}{\partial \theta} \\ + \hat{\mathbf{e}}_\phi \left( 1/a [2 \sinh^2 \eta \sin^2 \theta]^{1/2} \right) \frac{\partial}{\partial \phi}.$$

$$5.11 \quad \frac{4}{3}\pi R^3.$$

- 5.13 (b)  $\nabla f = -\hat{\rho}$ .  
 5.15 (a)  $\nabla T_{1,2,3} = -2(\hat{\mathbf{i}} + \hat{\mathbf{j}} + \hat{\mathbf{k}}) \Rightarrow -3.46 \text{ K/m}$ .  
 (b) 4.15 K.  
 (c) The rate of temperature decrease is getting larger the further

we move from the origin.

- 5.17  $v_{\max} = \left[ \frac{2}{m} \left\{ \frac{q(Q_1+Q_2)}{4\pi\epsilon_0} \left( \frac{1}{a} - \frac{1}{\sqrt{b^2+a^2}} \right) \right\} \right]^{\frac{1}{2}}$  at  $y = 0$ .  
 5.19 609 N.  
 5.21  $1.99 \times 10^{-25} \text{ kg}$ .  
 5.23  $h = G \frac{M_e m}{|E|} - R_e$ .  
 5.27 (a)  $\mathbf{F} = -A \frac{\hat{\mathbf{i}}x + \hat{\mathbf{j}}y + \hat{\mathbf{k}}z}{(x^2+y^2+z^2)^{3/2}}$ ,  
 (b)  $W = A/\sqrt{x_1^2 + y_1^2 + z_1^2}$ ,  
 (c)  $\mathbf{F} = -A \frac{\mathbf{r}}{r^3}$ .  
 5.29  $\frac{Q_1 Q_2}{4\pi\epsilon_0} \frac{1}{r} - \frac{Q_1 Q_2}{4\pi\epsilon_0} \frac{1}{r_0}$ .  
 5.31  $-\frac{Gm_1 m_2}{r}$ .  
 5.33 (b) 4.24 m/s, (c) +5.77, and  $x = -2.77 \text{ m}$ .  
 5.35  $x(t) = v_{0x} \sqrt{\frac{m}{a}} \sin \sqrt{\frac{a}{m}} t, y(t) = v_{0y} \sqrt{\frac{m}{b}} \sin \sqrt{\frac{b}{m}} t$ .

## Chapter 6

- 6.1 (a) 5 m/s (b) 3.45 m/s.  
 6.3  $v = \frac{m+M}{m} \sqrt{2gh}$ .  
 6.7 (a)  $v = v_0 m_0 / \left[ m_0^{4/3} + \frac{4kv_0 m_0}{3K^{2/3}} t \right]^{3/4}$  where  $k = \rho_d \pi$  and  $K = m/r^3$ .  
 (b)  $F = -\frac{k(v_0 m_0)^2}{K^{2/3}} \left[ 1 / \left( m_0^{4/3} + \frac{4kv_0 m_0}{3K^{2/3}} t \right) \right]$ .  
 6.9  $\cos^{-1} \left[ \left( \frac{m_M}{m_M + m_W} \right)^2 (0.13) - 1 \right]$ .  
 6.11  $kmV$ .  
 6.15  $v(t) = -gt + \frac{2mg}{k} \ln \frac{2m}{2m-kt}$ .  
 6.17 15 kg/s, 16.2 kg/s.  
 6.19  $t = 660 \text{ s} = 11 \text{ m}$ .  
 6.21 8.70 times the height from which it was dropped.  
 6.23  $\sqrt{12} \text{ m/s}$ ,  $30^\circ$ .  
 6.25 25 km/s.

## Chapter 7

- 7.1 (b) Total torque is zero so angular momentum is constant.  
 (c) Particles have the same linear momentum, so angular momentum is independent of the choice of origin.  
 7.5  $\mathbf{l} = -(1/2)v_{0x} F_e t^2 \hat{\mathbf{i}}$ .  
 7.7  $d = \frac{D\mu R}{h}$ .  
 7.9  $.51 \times 10^4 \text{ rad/s}$ .  
 7.13  $\frac{1}{2} M(R_2^2 + R_1^2)$ .

7.15  $\frac{5}{4}MR^2$ .

7.17 Number of turns =  $\omega_0^2 I \sqrt{\mu^2 + 1} / 4\pi a \mu mg$ ,  $t = (1 + \sqrt{2}) \frac{\omega_0 I \sqrt{\mu^2 + 1}}{a \mu mg}$ .

7.19 (a)  $W = \frac{d}{2}mg$ , (b)  $\omega_f = \sqrt{\omega_i^2 + gd/a^2}$ , (c)  $F = \frac{1}{2}mg$ .

7.21 (a)  $\omega = 0.09v/l$ . (b)  $\omega = \frac{0.2}{1.1} \frac{v}{l}$ .

## Chapter 8

8.1 Energy.

8.3 Yes.

## Chapter 9

9.1  $1.03 \times 10^6$  m/s.

9.3  $\sqrt{\frac{3\pi}{G\rho}}$ .

9.5  $-\frac{2GM}{R^2L} \left[ L - \sqrt{Z^2 + R^2} - \sqrt{(Z-L)^2 + R^2} \right]$ .

9.7  $\frac{2G\lambda m}{d}$ .

9.9  $-2G\rho r \hat{\mathbf{r}}$ .

9.11 Outside  $\Phi = -\frac{GM}{r}$ ,  $\mathbf{g} = -\frac{GM}{r^2} \hat{\mathbf{r}}$ ,

Inside  $\mathbf{g} = -GM \frac{r}{R^3} \hat{\mathbf{r}}$ ,  $\Phi = -\frac{GM}{2} \left[ \frac{3}{R} - \frac{r^2}{R^3} \right]$ .

9.13 (a)  $\Phi = \int -\frac{G\lambda ad\phi'}{s} = -\frac{GM}{s} = -\frac{GM}{\sqrt{z^2 + a^2}}$ ,

(b)  $\Phi = -\frac{GM}{r} \left[ 1 - \frac{1}{2} \frac{a^2}{r^2} \left( 1 + \frac{3}{2} \sin^2 \theta \right) \right]$ .

9.15 84 min.

9.17 (a) For sphere outside and inside,  $g = -\frac{GM}{r^2}$ ,  $g = -\frac{GM}{R^3}r$ .

(b) For shell outside and inside,  $g = -\frac{GM}{r^2}$ , 0.

9.19  $g = 2\pi G\sigma$  (towards plane).

9.21  $\frac{5kr^2}{4\pi G}$ . For the second field, the mass density  $\rho$  is a delta function, zero everywhere except at the origin.

## Chapter 10

10.1

n	r (Å)	E(eV)
1	0.53	-13.60
2	2.13	-3.40
3	4.76	-1.51
4	8.47	-0.85

10.5  $\Delta\tau = 3(2\pi GM)^{-2/3} T^{5/3} V \Delta V$ .

10.7 (a)  $\mathbf{r}'_1 = -\frac{m_2}{m_1+m_2} \mathbf{r}$ ,  $\mathbf{r}'_2 = +\frac{m_1}{m_1+m_2} \mathbf{r}$ .

(b)  $L = \frac{1}{2}(m_1 + m_2)\dot{R}^2 + \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} \dot{r}^2 + G \frac{m_1 m_2}{r}$ .

(c)  $\mu \ddot{r} - \mu r \dot{\theta}^2 + G \frac{m_1 m_2}{r^2} = 0$ ,  $\frac{d}{dt} (\mu r^2 \dot{\theta}) = 0$ .

(d)  $\ddot{r} - \frac{l^2}{\mu^2 r^3} = -G \frac{(m_1 + m_2)}{r^2}$ .

- (e)  $\tau^2 = \frac{4\pi^2}{G(m_1+m_2)}a^3$ .
- 10.9 (a)  $r = (a/2)(1 + \cos \theta)$ , (b)  $3\pi/8\sqrt{3ma^5/2K}$ .
- 10.13 1300 km.
- 10.21  $e = (v_{\max} - v_{\min}) / (v_{\min} + v_{\max})$ .

#### Chapter 11

- 11.1  $b^2/4m = k$ .
- 11.3  $k = 3.43 \times 10^4 \text{ N/m}$ ,  $b = 3.1 \times 10^3 \text{ kg/s}$ .
- 11.5  $t \leq \sqrt{0.6} / \sqrt{\frac{k}{m} - \frac{b}{2m}}$ .
- 11.7  $\gamma_2 x_0 + v_0 = 0$ .
- 11.11  $x(t) = (x_0 + A [ -(\omega_0^2 - \omega_d^2) + [\gamma_c A (\omega_0^2 - \omega_d^2) - A (\omega_d^2 b/m) ] t ] ) e^{-\gamma_c t} + A [ (\omega_0^2 - \omega_d^2) \cos \omega_d t + (\omega_d b/m) \sin \omega_d t ]$ .
- 11.13  $x(t) = A e^{-\gamma t} \cos(\omega_1 t + \theta) + \frac{F_0}{4a^2 m} (1 - e^{-at})$ .
- 11.15  $\omega = \sqrt{k \frac{m_1+m_2}{m_1 m_2}}$ .
- 11.19 Normal mode frequencies:  $\omega = \pm \sqrt{\frac{m_1+m_3}{m_3}} \sqrt{\frac{k_1}{m_1}}$ ,  $\omega = \pm \sqrt{\frac{m_2+m_3}{m_3}} \sqrt{\frac{k_2}{m_2}}$ .

#### Chapter 12

- 12.1 Work =  $\frac{1}{2} I \dot{\phi}^2 \Big|_i^f = \Delta T$ .
- 12.3  $\frac{9}{64} \sin^4 \frac{\theta_m}{2}$ .
- 12.5 (a)  $L = \frac{1}{2} m l^2 \dot{\theta}^2 - m l A \dot{\theta} f \sin \theta \sin ft + \frac{m}{2} A^2 f^2 \sin^2 ft - m g (-l \cos \theta + A \cos ft)$ .
- (b)  $\ddot{\theta} = \left[ \frac{A f^2}{l} \cos ft + \frac{g}{l} \right] \sin \theta$ .
- (c)  $\omega = \sqrt{\frac{A f^2}{l} \cos ft + \frac{g}{l}}$ .
- 12.7 (a) 2.85 s, (b) 2.02 m.
- 12.9  $1.73r$ .
- 12.11  $T = 2\pi \sqrt{m/2k}$ .
- 12.13  $\frac{4k_0}{\sqrt{gh}} F \left( \sin \frac{\theta_{\max}}{2} \right)$ .
- 12.15 4.08 rad/sec.
- 12.17  $T = \frac{2E}{l} - 3mg \cos \theta$ ,  $\cos^{-1} \left( \frac{2E}{3mgl} \right)$ .
- 12.19  $H = \frac{1}{2} \frac{p_\theta^2}{ml^2} + \frac{p_\phi^2}{2ml^2 \sin^2 \theta} + mgl \cos \theta$ ,  $\dot{p}_\phi = 0$ ,  $\dot{\phi} = \frac{2p_\phi}{ml^2 \sin^2 \theta}$ .

#### Chapter 13

- 13.3  $\mathbf{a} = \mathbf{a}''' + 2(\boldsymbol{\Omega} + \boldsymbol{\omega}) \times \mathbf{v}''' + 2\boldsymbol{\omega} \times (\boldsymbol{\Omega} \times \mathbf{r}''') + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_E)$ .
- 13.5  $a_{\text{cent}} = 0$ ,  $a_{\text{cor}} = -2\frac{V^2}{R} \hat{\mathbf{x}}'$ .
- 13.7  $d = \frac{2h}{3g} \Omega \sin \lambda \sqrt{2h \left[ \frac{h}{2} \Omega^2 \cos^2 \lambda + 1 \right]} = 0.79 \text{ cm}$ .
- 13.9 3.5 km South and 3.5 km East of the expected target. It is in flight 2.3 seconds longer than expected.

- 13.11 76.7 km/hr.  
 13.13 32 m.  
 13.15  $3.3 \times 10^{-3}$  rad.  
 13.17 (a)  $2\Omega v \hat{\phi}$ , (b)  $2\Omega v \hat{r}$ , (c) 0, (d)  $d_\phi = -\frac{4}{3} \frac{\Omega v_0^3}{g_e^2}$ .  
 13.19 28.8 m (North).  
 13.21 (a)  $\omega_0 = \sqrt{\frac{k}{m}}$ ; (b)  $r(t) = a + \eta_0 \cos(2\omega_0 t)$ .

#### Chapter 14

- 14.1  $\tan \alpha = \frac{1}{2}(\tan \theta - \tan \phi)$ ,  $T_1 = [mg / (\sin \theta + \cos \theta \tan \phi)]$ ,  
 $T_2 = [mg / (\sin \theta + \cos \theta \tan \phi)] \frac{\cos \theta}{\cos \phi}$ .  
 14.3 71.8°.  
 14.7 1.67 Mg at a point 0.86l along the rod.  $\theta = -13.87^\circ$ .  
 14.9 (a) CW rotation and linear acceleration along the x axis.  
 (b) -10 newtons acting at a distance  $y = 1.866$  m from x axis.  
 14.15  $r_{cg} = [(a/2)^2 + y^2]^{3/4} / y^{1/2}$ .  
 14.17 7.85 m.  
 14.19  $9.77 \times 10^{-3}$  K/m.

#### Chapter 15

15.5 The rotation has a magnitude of  $53.27^\circ$ . The axis of rotation is in the equatorial plane and directed at an angle of  $119^\circ 47' - 90^\circ$  west of Greenwich.

15.7  $\begin{pmatrix} 1 \\ 0 \\ 3 \end{pmatrix}, \begin{pmatrix} -3/\sqrt{35} \\ 5/\sqrt{35} \\ 1/\sqrt{35} \end{pmatrix}, \begin{pmatrix} -3/\sqrt{14} \\ -2/\sqrt{14} \\ 1/\sqrt{14} \end{pmatrix}$

15.9 (a) A reflection through the x-axis. (b) A rotation of  $180^\circ$  about the z-axis.

15.11  $\lambda = 3$  and  $\lambda = -1$ .  
 $\begin{pmatrix} 2/\sqrt{5} \\ 1/\sqrt{5} \end{pmatrix}, \begin{pmatrix} 2/\sqrt{5} \\ -1/\sqrt{5} \end{pmatrix}, \begin{pmatrix} 2/\sqrt{5} & 2/\sqrt{5} \\ 1/\sqrt{5} & -1/\sqrt{5} \end{pmatrix}$

#### Chapter 16

- 16.3  $5Ma^2, 5Ma^2, 8Ma^2$ ,  
 $\begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \\ 0 \end{pmatrix}, \begin{pmatrix} -1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} -1/\sqrt{2} \\ 1/\sqrt{2} \\ 0 \end{pmatrix}$ .  
 16.9  $T = \frac{1}{2}I_1 [\dot{\theta}^2 + \dot{\phi}^2 \sin^2 \theta] + \frac{1}{2}I_3 (\dot{\psi} + \dot{\phi} \cos \theta)^2$ ,  
 $\mathbf{L} = (I_1 \dot{\phi} \sin \theta \sin \psi) \hat{\mathbf{e}}_1 + (I_1 \dot{\phi} \sin \theta \cos \psi) \hat{\mathbf{e}}_2 + (I_3 (\dot{\psi} + \dot{\phi} \cos \theta)) \hat{\mathbf{e}}_3$ .  
 16.11 (a)  $p_\phi = I_3 \cos \theta_1 \omega_3$ ,  $p_\psi = I_3 \omega_3$ ,  
 $V'(\theta) = \frac{I_3^2 \omega_3^2 (\cos \theta_1 - \cos \theta)^2}{2I_1 \sin^2 \theta} + mgd \cos \theta + \frac{1}{2}I_3 \omega_3^2$ ,  
 $E = mgd \cos \theta + \frac{1}{2}I_3 \omega_3^2$ .

$$(b) \cos \theta_2 = \frac{1}{2\alpha} \left[ 1 - (1 - 4\alpha \cos \theta_1 + 4\alpha^2)^{1/2} \right].$$

16.13  $\dot{\phi} = 2.18 \text{ rad/s.}$

Chapter 17

17.3  $y(x, t) = A \sin \frac{\pi x}{L} \cos \sqrt{F/\rho} \frac{\pi}{L} t.$

17.5  $y(x, t) \simeq -\frac{L^2}{24R} + \sum_n \frac{L^2}{2\pi^2 n^2 R} (-1)^n \cos \frac{2\pi n x}{L} \cos \omega_n t$  where  $\omega_n = n\pi c/L.$

17.7 (a)  $\rho \frac{\partial^2 y}{\partial t^2} + b dx \frac{\partial y}{\partial t} - F \frac{\partial}{\partial x} \left[ \frac{\partial y}{\partial x} \right] = 0.$   
 (b)  $\rho \ddot{\phi}_m + b \dot{\phi}_m + [Fm^2 \pi^2 / L^2] \phi_m = 0.$   
 (c)  $\phi_m = e^{-bt/2\rho} (A_m \sin \omega'_m t + B_m \cos \omega'_m t)$  where  $\omega'_m = \sqrt{\frac{m^2 \pi^2 F}{L^2 \rho} - \frac{b^2}{4\rho^2}}.$

17.9 (a)  $\ddot{Q}_n + \frac{\pi^2 F_0}{\rho l} n^2 Q_n = 0$  (b)  $Q_n = A_n \cos \sqrt{\frac{\pi^2 F_0}{\rho l}} nt + B_n \sin \sqrt{\frac{\pi^2 F_0}{\rho l}} nt.$

Chapter 18

18.1 Assume  $x_1$  and  $x_2$  are measured in opposite directions from the equilibrium points. Mass matrix is  $m \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$  and the potential matrix is

$$k \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}.$$

18.3  $\omega^2 = \frac{k}{m} \begin{Bmatrix} 2.62 \\ 0.38 \end{Bmatrix}, \rho^{(1)} = \frac{1}{\sqrt{1.384m}} \begin{pmatrix} 1 \\ -0.62 \end{pmatrix}, \rho^{(2)} = \frac{1}{\sqrt{3.62m}} \begin{pmatrix} 1 \\ 1.62 \end{pmatrix}.$

18.5  $\frac{k}{m}, 2\frac{k}{m}, 3\frac{k}{m}.$

18.7 (a)  $L = \frac{1}{2} m (\dot{\eta}_1^2 + \dot{\eta}_2^2) - k\eta_1^2 + k\eta_2\eta_1 - k\eta_2^2,$

$$\ddot{\eta}_1 + 2\frac{k}{m}\eta_1 - \frac{k}{m}\eta_2 = 0,$$

$$\ddot{\eta}_2 + 2\frac{k}{m}\eta_2 - \frac{k}{m}\eta_1 = 0.$$

18.9  $\eta_1(t) = C_1 \cos(\omega_1 t + \phi_1) + C_2 \cos(\omega_2 t + \phi_2) + K_1 \sin \omega t,$   
 $\eta_2(t) = C_1 \cos(\omega_1 t + \phi_1) - C_2 \cos(\omega_2 t + \phi_2) + K_2 \sin \omega t.$

18.11  $\mathcal{M} = \begin{pmatrix} m+M & -M \\ -M & m+M \end{pmatrix},$

$$\mathcal{V} = \begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix},$$

$$\omega^2 = \begin{Bmatrix} \frac{k}{m} \\ \frac{k}{m} \frac{m}{m+2M} \end{Bmatrix}.$$

18.13 (a)  $L = \frac{1}{2} m \sum_{i=1}^N \dot{\eta}_i^2 - \frac{mg}{2l} \sum_{i=1}^N \eta_i^2 - \frac{1}{2} k \sum_{i=1}^{N-1} [(\eta_i - \eta_{i-1})^2 + (\eta_{i+1} - \eta_i)^2],$

(b)  $m\ddot{\eta}_i + \frac{mg}{l}\eta_i + 2k\eta_i - k(\eta_{i+1} + \eta_{i-1}) = 0,$

(c)  $\omega^2 = \frac{g}{l} + 4\frac{k}{m} \sin^2 \frac{ka}{2}.$

Chapter 19

19.1 (a)  $x^* = 2.175 \text{ m}, t^* = 1.25 \text{ ns.}$  (b)  $x^* = 1.74 \text{ m}, t^* = 7 \times 10^{-9} \text{ s.}$

19.5 (a)  $x^* = -1.73 \times 10^8 \text{ m}, t^* = 2.87 \text{ sec.}$

- (b)  $x^* = 8.66 \times 10^8$  m,  $t^* = 4.04$  s.
- 19.9  $\frac{\sqrt{3}}{2}c$ .
- 19.11  $0.8c$ .
- 19.13 6.4 cm.
- 19.15 (a)  $0.83c$  (b)  $5.53\mu s$ .
- 19.17 (b)  $f = 0.151$  (c)  $9.64^\circ$ .
- (d) The same amount of light is concentrated into a smaller cone.
- 19.19  $v = \frac{1}{\sqrt{2}}c = 0.707c$ ,  $T = 0.414m_0c^2$ .
- 19.21  $T = 1.35 \times 10^{-9}$  J,  $p = 4.99 \times 10^{-20}$  kg m/s.
- 19.23 (a)  $p_f = 1.33m_0c$ , (b)  $v_f = 0.553c$ , (c) classically,  $v_f = 0.4c$ .
- 19.25  $2.31 \times 10^{-10}$  g.
- 19.27 Fractional change in area = 0.6.