Classical Dynamics: Example Sheet 3

Dr David Tong, November 2005

1. Show that the effect of three rotations by Euler angles results in the relationship $\mathbf{e}_a = R_{ab}\tilde{\mathbf{e}}_b$ between the body frame axes $\{\mathbf{e}_a\}$ and the space frame axes $\{\tilde{\mathbf{e}}\}$ where the orthogonal matrix R is

$$R = \left(\begin{array}{ccc} \cos\psi\cos\phi - \cos\theta\sin\phi\sin\psi & \sin\phi\cos\psi + \cos\theta\sin\psi\cos\phi & \sin\theta\sin\psi \\ -\cos\phi\sin\psi - \cos\theta\cos\psi\sin\phi & -\sin\psi\sin\phi + \cos\theta\cos\psi\cos\phi & \sin\theta\cos\psi \\ \sin\theta\sin\phi & -\sin\theta\cos\phi & \cos\theta \end{array} \right)$$

Use this to confirm that the angular velocity $\boldsymbol{\omega}$ can be expressed in terms of Euler angles as

$$\boldsymbol{\omega} = [\dot{\phi}\sin\theta\sin\psi + \dot{\theta}\cos\psi]\mathbf{e}_1 + [\dot{\phi}\sin\theta\cos\psi - \dot{\theta}\sin\psi]\mathbf{e}_2 + [\dot{\psi} + \dot{\phi}\cos\theta]\mathbf{e}_3 \qquad (1)$$

in the body frame $\{\mathbf{e}_a\}$. Or, alternatively, as

$$\boldsymbol{\omega} = [\dot{\psi}\sin\theta\sin\phi + \dot{\theta}\cos\phi]\tilde{\mathbf{e}}_1 + [-\dot{\psi}\sin\theta\cos\phi + \dot{\theta}\sin\phi]\tilde{\mathbf{e}}_2 + [\dot{\phi} + \dot{\psi}\cos\theta]\tilde{\mathbf{e}}_3 \qquad (2)$$

in the space frame $\{\tilde{\mathbf{e}}_a\}$.

2. The physicist Richard Feynman tells the following story:

> "*I was in the cafeteria and some guy, fooling around, throws a plate in the air. As the plate went up in the air I saw it wobble, and I noticed the red medallion of Cornell on the plate going around. It was pretty obvious to me that the medallion went around faster than the wobbling.*
>
> *I had nothing to do, so I start figuring out the motion of the rotating plate. I discover that when the angle is very slight, the medallion rotates twice as fast as the wobble rate – two to one. It came out of a complicated equation!*
>
> *I went on to work out equations for wobbles. Then I thought about how the electron orbits start to move in relativity. Then there's the Dirac equation in electrodynamics. And then quantum electrodynamics. And before I knew it....the whole business that I got the Nobel prize for came from that piddling around with the wobbling plate.*"

Feynman was right about quantum electrodynamics. But what about the plate?

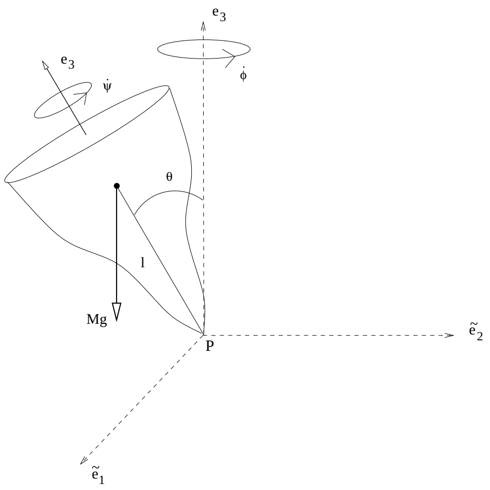

Figure 1: The Euler angles for the heavy symmetric top

3. Consider a heavy symmetric top of mass M, pinned at point P which is a distance l from the centre of mass. The principal moments of inertia about P are I_1, I_1 and I_3 and the Euler angles are shown in the figure. The top is spun with initial conditions $\dot{\phi} = 0$ and $\theta = \theta_0$. Show that θ obeys the equation of motion,

$$I_1 \ddot{\theta} = -\frac{\partial V_{\rm eff}(\theta)}{\partial \theta} \tag{3}$$

where

$$V_{\rm eff}(\theta) = \frac{I_3^2 \omega_3^2}{2I_1} \frac{(\cos\theta - \cos\theta_0)^2}{\sin^2\theta} + Mgl\cos\theta \tag{4}$$

Suppose that the top is spinning very fast so that

$$I_3 \omega_3 \gg \sqrt{MglI_1} \tag{5}$$

Show that θ_0 is close to the minimum of $V_{\rm eff}(\theta)$. Use this fact to deduce that the top nutates with frequency

$$\Omega \approx \frac{\omega_3 I_3}{I_1} \tag{6}$$

and draw the subsequent motion.

4. Throw a book in the air. If the principal moments of inertia are $I_1 > I_2 > I_3$, convince yourself that the book can rotate in a stable manner about the principal axes $\mathbf{e}_1$ and $\mathbf{e}_3$, but not about $\mathbf{e}_2$.

Use Euler's equations to show that the energy E and the total angular momentum $\mathbf{L}^2$ are conserved. Suppose that the initial conditions are such that

$$\mathbf{L}^2 = 2I_2E \tag{7}$$

with the initial angular velocity $\boldsymbol{\omega}$ perpendicular to the intermediate principal axes $\mathbf{e}_2$. Show that $\boldsymbol{\omega}$ will ultimately end up parallel to $\mathbf{e}_2$ and derive the characteristic time taken to reach this steady state.

5. A rigid lamina (i.e. a two dimensional object) has principal moments of inertia about the centre of mass given by,

$$I_1 = (\mu^2 - 1) \qquad I_2 = (\mu^2 + 1) \quad , \quad I_3 = 2\mu^2 \tag{8}$$

Write down Euler's equations for the lamina moving freely in space. Show that the component of the angular velocity in the plane of the lamina (i.e. $\sqrt{\omega_1^2 + \omega_2^2}$) is constant in time.

Choose the initial angular velocity to be $\boldsymbol{\omega} = \mu N\mathbf{e}_1 + N\mathbf{e}_3$. Define $\tan\alpha = \omega_2/\omega_1$, which is the angle the component of $\boldsymbol{\omega}$ in the plane of the lamina makes with $\mathbf{e}_1$. Show that it satisfies

$$\ddot{\alpha} + N^2 \cos\alpha \sin\alpha = 0 \tag{9}$$

and deduce that at time t,

$$\boldsymbol{\omega} = [\mu N \mathrm{sech}\, Nt]\mathbf{e}_1 + [\mu N \tanh Nt]\mathbf{e}_2 + [N \mathrm{sech}\, Nt]\mathbf{e}_3 \tag{10}$$

6. The Lagrangian for the heavy symmetric top is

$$L = \tfrac{1}{2}I_1\left(\dot{\theta}^2 + \dot{\phi}^2\sin^2\theta\right) + \tfrac{1}{2}I_3(\dot{\psi} + \dot{\phi}\cos\theta)^2 - Mgl\cos\theta \tag{11}$$

Obtain the momenta p_θ, p_ϕ and p_ψ and the Hamiltonian $H(\theta, \phi, \psi, p_\theta, p_\phi, p_\psi)$.

7. A system with two degrees of freedom x and y has the Lagrangian,

$$L = x\dot{y} + y\dot{x}^2 + \dot{x}\dot{y} \tag{12}$$

Derive Lagrange's equations. Obtain the Hamiltonian $H(x, y, p_x, p_y)$. Derive Hamilton's equations and show that they are equivalent to Lagrange's equations.