

Classical Mechanics Problem 1: Central Potential
Solution

a) Integrals of motion for a central potential $V(r)$:

$$\begin{aligned} \text{Angular Momentum} \quad L &= r v_\phi = r^2 \dot{\phi} \\ \text{Energy per unit mass} \quad E &= \frac{1}{2} (\dot{r}^2 + v_\phi^2) + V(r) = \frac{1}{2} \dot{r}^2 + V_{\text{eff}}(r) \end{aligned}$$

where v_ϕ is the tangential velocity and V_{eff} is defined as

$$V_{\text{eff}}(r) = V(r) + \frac{L^2}{2r^2}$$

If the orbit is circular, the distance of the test body from the origin is invariant: $\dot{r} = 0$, which implies that the body is always at the equilibrium-distance:

$$\frac{dV_{\text{eff}}}{dr} = 0 \quad \Rightarrow \quad \frac{dV}{dr} = \frac{L^2}{r^3} = \frac{v_\phi^2}{r} = r \dot{\phi}^2$$

then

$$\dot{\phi} = \omega_\phi = \frac{L}{r^2} = \left(\frac{1}{r} \frac{dV}{dr} \right)^{1/2}$$

so for the period we get

$$\boxed{T_\phi = \frac{2\pi}{\omega_\phi} = 2\pi \left(\frac{1}{r} \frac{dV}{dr} \right)^{-1/2}}$$

b) Write the orbit as in the statement of the problem:

$$r(t) = r_0 + \epsilon(t) \quad \text{with} \quad \frac{dV_{\text{eff}}}{dr}(r_0) = 0 \quad \text{and} \quad \epsilon^2 \ll r_0^2.$$

The energy per unit mass is now $E = \frac{1}{2} \dot{\epsilon}^2 + V_{\text{eff}}(r_0 + \epsilon)$, and since ϵ is small we may Taylor-expand the potential as

$$V_{\text{eff}}(r_0 + \epsilon) = V_{\text{eff}}(r_0) + \underbrace{\frac{dV_{\text{eff}}}{dr}(r_0)}_{=0} \epsilon + \frac{1}{2} \frac{d^2 V_{\text{eff}}}{dr^2}(r_0) \epsilon^2 + \mathcal{O}(\epsilon^3)$$

so then

$$E - V_{\text{eff}}(r_0) = \frac{1}{2} \dot{\epsilon}^2 + \frac{1}{2} \frac{d^2 V_{\text{eff}}}{dr^2}(r_0) \epsilon^2 + \mathcal{O}(\epsilon^3) = \text{const.}$$

In the above equation we readily recognize the equation of the simple harmonic oscillator with

$$\boxed{\omega_\epsilon = \left(\frac{d^2 V_{\text{eff}}}{dr^2} \right)_{r=r_0}^{1/2}}$$

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