PHY3110 SP23 Notes

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0 Introduction

Grading: 30% homework, 30% midterm, 40% final.

Textbooks:

- H. Goldstein, C. Poole, J. Safko, Classical Mechanics, 3rd Edition, Pearson.
- J.R. Taylor, Classical Mechanics, University Science Books.
- T.W.B. Kibble, F.H. Berkshire, Classical Mechanics, 5th Edition, Imperial College Press.
- 梁昆淼，力学（下册）理论力学，4th Edition，高等教育出版社.

Classical mechanics describe the motion of macroscopic objects, which are not extremely massive and not extremely fast.

1 Newtonian Mechanics

Vectorial quantities of motion: position $\mathbf{r}$, velocity $\mathbf{v}$, force $\mathbf{F}$, momentum $\mathbf{p} = m\mathbf{v}$, angular momentum $\mathbf{L} = \mathbf{r} \times \mathbf{p}$. Equations of motion are derived from those vector quantities.

Analytical mechanics uses scalar quantities of motion

- Kinetic energy $T = \frac{1}{2}m\mathbf{v}^2$
- Potential energy $V = V(\mathbf{r})$

Equations of motion are derived from those scalar quantities.

1.1 Newton's Laws

Theorem 1.1 (Newton's 2$^{\text{nd}}$ law)**.**

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = m\mathbf{a} \tag{1}$$

The formula is valid in an inertial frame.

Angular momentum $\mathbf{L}$ and torque $\mathbf{N}$ are also related

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{r} \times \mathbf{p}) = \mathbf{r} \times \mathbf{F} = \mathbf{N} \tag{2}$$

Work done by external forces

$$W_{12} = \int_1^2 \mathbf{F}\,\mathrm{d}\mathbf{s} = \int_1^2 m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}\,\mathrm{d}\mathbf{s} = \int_1^2 m\mathbf{v}\,\mathrm{d}\mathbf{v} = \frac{1}{2}m\mathbf{v}^2\Big|_1^2 \tag{3}$$

Define a scalar function $V(\mathbf{r})$, then $\mathbf{F} = -\nabla V(\mathbf{r})$ is a conservative force.

$$\oint \mathbf{F}\,\mathrm{d}\mathbf{s} = 0 \tag{4}$$

Center of mass of the system

$$\mathbf{R} = \frac{\sum_i m_i \mathbf{r}_i}{\sum_i m_i} = \frac{\sum_i m_i \mathbf{r}_i}{M} \tag{5}$$

Total momentum

$$\mathbf{P} = \sum_i m_i \mathbf{p}_i = M\dot{\mathbf{R}} \tag{6}$$

Hence $\mathbf{P}$ is conserved if external force $\mathbf{F}^{(e)}$ is zero.
Total angular momentum

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t} \sum_i \mathbf{r}_i \times \mathbf{p}_i = \sum_i \mathbf{r}_i \times \left(\mathbf{F}_i^{(e)} + \sum_j \mathbf{F}_{ij} \right) = \sum_i \mathbf{r}_i \times \mathbf{F}_i^{(e)} + \sum_{ij} \mathbf{r}_i \times \mathbf{F}_{ij}$$

Since $\mathbf{r}_{ij}$ parallel to $\mathbf{F}_i j$, then

$$\sum_{ij} \mathbf{r}_i \mathbf{F}_{ij} = \frac{1}{2} \sum_{ij} \mathbf{r}_{ij} \times \mathbf{F}_{ji} = 0 \tag{7}$$

Therefore

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \mathbf{N}^{(e)} \tag{8}$$

Decomposition of the angular momentum

$$\mathbf{L} = \sum_i \mathbf{r}_i \times \mathbf{p}_i = \sum_i (\mathbf{R} + \mathbf{r}_i) \times m_i (\mathbf{V} + \mathbf{v}_i') = \sum_i \mathbf{R} \times m_i \mathbf{V} + \sum_i \mathbf{r}_i' \times m_i \mathbf{v}_i' \tag{9}$$

1.2 Constraints

Holonomic constraint

$$f(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N, t) = 0 \tag{10}$$

Example: rigid body

$$(\mathbf{r}_i - \mathbf{r}_j)^2 - c_{ij}^2 = 0 \tag{11}$$

Example: non-sliding cylinder

$$\dot{x} - R\dot{\theta} = 0 \Rightarrow x - R\theta = \mathrm{const}$$

A constraint of the form

$$\sum_i g_i(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n)\, \mathrm{d}\mathbf{x}_i = 0 \Rightarrow \mathrm{d}G(\mathbf{x}_1, \dots) = 0 \Rightarrow G(\mathbf{x}_1, \dots) = \mathrm{const} \tag{12}$$

Non-holonomic constraint: cannot be written in the form of holonomic constraint.

1.3 Generalized coordinates

Suppose we have a N-particle system, we will have $3N$ DOFs. With k constraints, we will have $3N-k$ DOFs. Define $q_1, \dots, q_{3N-k}$ generalized coordinates, we have

$$\mathbf{r}_i = \mathbf{r}_i(q_1, \dots, q_{3N-1}, t) \tag{13}$$

2 Lagrange Formalism

2.1 D'Alembert's Principle

Hint from the rigid body: internal forces of constraints do not work.

Virtual displacement: $\delta\mathbf{r}_i$ is consistent with the constraints imposed on the system at a given time

$$\mathbf{r}_i \to \mathbf{r}_i + \delta\mathbf{r}_i \tag{14}$$

Theorem 2.1 (D'Alembert's principle). Consider a system in equilibrium

$$\mathbf{F}_i = 0 \Rightarrow \sum_i \mathbf{F}_i \cdot \delta\mathbf{r}_i = 0 \tag{15}$$

Separate $\mathbf{F}_i = \mathbf{F}_i^{(a)} + \mathbf{f}_i$ where $\mathbf{f}_i$ is the constraint force. Hence

$$\sum_i (\mathbf{F}_i^{(a)} + \mathbf{f}_i) \cdot \delta\mathbf{r}_i = 0 \Rightarrow \sum_i \mathbf{F}_i^{(a)} \cdot \delta\mathbf{r}_i = 0 \tag{16}$$

For a system moving under external forces

$$\mathbf{F}_i - \dot{\mathbf{p}}_i = 0 \Rightarrow \sum_i (\mathbf{F}_i - \dot{\mathbf{p}}_i)\delta\mathbf{r}_i = 0 \Rightarrow \sum_i (\mathbf{F}_i^{(a)} - \dot{\mathbf{p}}_i)\delta\mathbf{r}_i = 0 \tag{17}$$

For holonomic constraints

$$\mathbf{r}_i = \mathbf{r}_i(q_1, \dots, q_n, t), \quad \mathbf{v}_i = \frac{\mathrm{d}\mathbf{r}_i}{\mathrm{d}t} = \frac{\partial \mathbf{r}_i}{\partial t} + \sum_j \frac{\partial \mathbf{r}_i}{\partial q_j}\dot{q}_j, \quad \delta\mathbf{r}_i = \sum_j \frac{\partial \mathbf{r}_i}{\partial q_j}\delta q_j \tag{18}$$

Define generalized force Q_j

$$\sum_i \mathbf{F}_i \delta\mathbf{r}_i = \sum_{ij} \mathbf{F}_i \frac{\partial \mathbf{r}_i}{\partial q_j}\delta q_j = \sum_j Q_j \delta q_j \tag{19}$$

Then

$$\sum_i \dot{\mathbf{p}}_i \cdot \delta\mathbf{r}_i = \sum_{ij} m_i \ddot{\mathbf{r}}_i \cdot \frac{\partial \mathbf{r}_i}{\partial q_j}\delta q_j = \sum_{ij} \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(m_i \dot{\mathbf{r}}_i \cdot \frac{\partial \mathbf{r}_i}{\partial q_j}\right) - m_i \dot{\mathbf{r}}_i \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial \mathbf{r}_i}{\partial q_j}\right]\delta q_j \tag{20}$$

$$= \sum_i \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j}\right]\delta q_j = \sum_j Q_j \delta q_j \tag{21}$$

$$\tag{22}$$

Hence $\forall j$ we have

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} - Q_j = 0 \tag{23}$$

Let the potential energy $V = V(\mathbf{r}_i, \dots) = V(q_j, \dots)$, then we have

$$Q_j = \sum_i \mathbf{F}_i \frac{\partial \mathbf{r}_i}{\partial q_j} = \sum_i -\nabla_i V \frac{\partial \mathbf{r}_i}{\partial q_j} = -\frac{\partial V}{\partial q_j} \tag{24}$$

Therefore

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial (T-V)}{\partial \dot{q}_j}\right) - \frac{\partial (T-V)}{\partial q_j} - Q_j = 0 \tag{25}$$

Theorem 2.2 (Langrange's equation)**.** Define $L = T - V$, then

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = 0 \tag{26}$$

The choice of Lagrangian is not unique, L' where

$$L' = L + \frac{\mathrm{d}F(q,t)}{\mathrm{d}t} \tag{27}$$

will give the same equations of motion as L.

Example 2.1 (Lagrange's formalism)**.**

1) For a single particle moving under force $\mathbf{F}$

$$L(\mathbf{x}, \dot{\mathbf{x}}, t) = \frac{1}{2} m \dot{\mathbf{x}}^2 + \mathbf{F} \cdot \mathbf{x}$$

2) Motion in a 2D plane using polar coordinates

$$L(r, \theta, \dot{r}, \dot{\theta}, t) = \frac{1}{2} m(\dot{r}^2 + r^2\dot{\theta}^2) + F \cdot \mathbf{r}$$

Generalized forces

$$\begin{aligned} Q_r &= \mathbf{F} \cdot \frac{\partial \mathbf{r}}{\partial r} = \mathbf{F} \cdot \mathbf{e}_r \\ Q_\theta &= \mathbf{F} \cdot \frac{\partial \mathbf{r}}{\partial \theta} = \mathbf{F} \cdot r\mathbf{e}_\theta \end{aligned}$$

where

$$\mathbf{e}_r = \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \quad \mathbf{e}_\theta = \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

Equations of motion

$$\begin{aligned} m\ddot{r} - mr\dot{\theta}^2 &= \mathbf{F} \cdot \mathbf{e}_r \\ mr^2\ddot{\theta} + 2mr\dot{r}\dot{\theta} &= r\mathbf{F}_\theta \end{aligned}$$

3) Atwood's machine

$$L = \frac{1}{2}(M_1 + M_2)\dot{x}^2 + M_1 g x + M_2 g(l - x)$$

The equation of motion is

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} = 0$$
$$\Rightarrow (M_1 + M_2)\ddot{x} = (M_1 - M_2)g$$

Suppose we have a potential dependent on velocity (generalized potential) and the generalized force is defined as

$$U = U(q_j, \dot{q}_j), \quad Q_j = -\frac{\partial U}{\partial q_j} + \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial U}{\partial \dot{q}_j} \tag{28}$$

Define $L = T - U$, then we still have

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_j} - \frac{\partial L}{\partial q_j} = 0 \tag{29}$$

Example 2.2 (Lorentz force on a moving charge)**.** The Lorentz force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Define the scalar and vector potentials

$$E = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

Hence

$$\mathbf{F} = q\left[-\nabla\phi - \frac{\partial \mathbf{A}}{\partial t} + \mathbf{v} \times (\nabla \times \mathbf{A})\right]$$

2.2 Hamilton's principle, variational principle

Configuration space: a space formed by the set of generalized coordinates.

$$(q_1, q_2, \dots, q_n) \text{ as function of } t \tag{30}$$

Theorem 2.3 (Hamilton's principle)**.** Define the action integral I, where $L = T - V$ or $L = T - U$ (U is the generalized potential)

$$I = \int_{t_1}^{t_2} L \, \mathrm{d}t \tag{31}$$

Then the variation of the action integral equals to zero

$$\delta I = \delta \int_{t_1}^{t_2} L(q_1, \dots, q_n, \dot{q}_1, \dots, \dot{q}_n) \, \mathrm{d}t = 0 \tag{32}$$

Add small variation on the path

$$q_i(t, \alpha) = q_i(t) + \alpha\eta(t) \tag{33}$$

where $\eta(t_1) = \eta(t_2) = 0$. Then the action will be the function of α, $I = I(\alpha)$. Hence

$$\delta I = \int_{t_1}^{t_2} \left(\sum_i \frac{\partial L}{\partial q_i} \delta q_i + \frac{\partial L}{\partial \dot{q}_i} \delta \dot{q}_i \right) \mathrm{d}t \tag{34}$$

Change the order of differentiation $\delta \dot{q}_i = \mathrm{d}\delta q_i / \mathrm{d}t$, then

$$\delta I(\alpha) = \int_{t_1}^{t_2} \sum_i \left[\frac{\partial L}{\partial q_i} \delta q_i - \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{\partial L}{\partial \dot{q}_i} \right) \delta q_i \right] \mathrm{d}t + \sum_i \frac{\partial L}{\partial \dot{q}_i} \delta q \Big|_{t_1}^{t_2} \tag{35}$$

$$= \int_{t_1}^{t_2} \sum_i \left[\frac{\partial L}{\partial q_i} - \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{\partial L}{\partial \dot{q}_i} \right) \right] \delta q_i \, \mathrm{d}t = 0 \tag{36}$$

$$\Rightarrow \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q_i} = 0 \tag{37}$$

Example 2.3 (Shortest path problem). $y = y(x)$, $\mathrm{d}s = \sqrt{\mathrm{d}x^2 + \mathrm{d}y^2}$, then the action integral (path) is

$$I = \int_1^2 \mathrm{d}s = \int_1^2 \sqrt{1 + \dot{y}^2} \, \mathrm{d}x \tag{38}$$

Apply the Lagrange's equation we get

$$\frac{\mathrm{d}}{\mathrm{d}x} \frac{\mathrm{d}\sqrt{1 + \dot{y}^2}}{\mathrm{d}\dot{y}} = 0 \Rightarrow \frac{\mathrm{d}\dot{y}}{\mathrm{d}x} = 0 \Rightarrow y = ax + b \tag{39}$$

Example 2.4 (Solid of revolution). Differential of area $2\pi x \, \mathrm{d}s = 2\pi x \sqrt{1 + \dot{y}^2} \, \mathrm{d}x$, then the total area is

$$\int_1^2 2\pi x \sqrt{1 + \dot{y}^2} \, \mathrm{d}x \tag{40}$$

Define the Lagrangian $L(x, y, \dot{y}) = 2\pi x \sqrt{1 + \dot{y}^2}$, by Lagrange's equation we can get

$$\frac{x\dot{y}}{\sqrt{1 + \dot{y}^2}} = \text{const} \Rightarrow y = a \cosh \frac{x}{a} + b \tag{41}$$

Example 2.5 (The curve of fastest descent). Question: along which trajectory from point 1 to point 2, the time is shortest? The total time is

$$T = \int_1^2 \frac{\mathrm{d}s}{v} = \int_1^2 \frac{\mathrm{d}s}{\sqrt{2gy}} \tag{42}$$

According to Newton's laws we have $y = gv^2$, then

$$T = \int_1^2 \frac{\sqrt{1 + \dot{y}^2}}{\sqrt{2gy}} \, \mathrm{d}x \tag{43}$$

Then we have $L(x, y, \dot{y})$ and we get check drivation

$$\frac{\dot{y}}{2y} + \frac{y\ddot{y}}{1 + \dot{y}^2} = 0 \tag{44}$$

$$\Rightarrow \frac{\mathrm{d}}{\mathrm{d}x}\ln[y(1+\dot{y}^2)] = 0 \tag{45}$$

which means that $y(1+\dot{y}^2) = \text{const}$. The solution is $x = a(\theta - \sin\theta)$, $y = a(1-\cos\theta)$.

2.3 Constraint

Holonomic constraints

$$f(q_1, \dots, q_n, t) = 0 \tag{46}$$

Non-holonomic constraints

$$f(q_1, \dots, q_n; \dot{q}_1, \dots, \dot{q}_n; t) = 0 \tag{47}$$

Sometimes we can convert $f(\dot{q}_i) = 0$ to $f'(q_i) = 0$.

Example 2.6 (Rolling cylinder)**.** Rolling cylinder without sliding has the constraint

$$\dot{x} - R\dot{\theta} = 0 \Rightarrow x - R\theta = \text{const} \tag{48}$$

A commonly encountered type of non-holonomic constraint is linear constraint equations

$$\sum_{k=1}^{n} a_{ik}\frac{\mathrm{d}q_k}{\mathrm{d}t} + a_i t = 0 \tag{49}$$

For the virtual displacement δq_i

$$\sum_{k=1}^{n} a_{ik}\delta q_k = 0 \tag{50}$$

Suppose q_i are not independent, then the Euler-Lagrange's equation could not hold.

$$\int_{t_1}^{t_2}\sum_i\left[\frac{\partial L}{\partial q_i} - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right)\right]\delta q_i\,\mathrm{d}t = 0 \nRightarrow \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q_i} = 0$$

Include the constraint equation of q_i into the equation

$$\sum_{k=1}^{n} a_{ik}\delta q_k = 0 \Rightarrow \sum_{i=1}^{m}\lambda_i\sum_{k=1}^{n} a_{ik}\delta q_k = 0 \tag{51}$$

Hence

$$\int_{t_1}^{t_2}\sum_{k=1}^{n}\left[\frac{\partial L}{\partial q_k} - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_k}\right) + \sum_{i=1}^{m}\lambda_i a_{ik}\right]\delta q_k\,\mathrm{d}t = 0$$

Let $q_1, \dots, q_{n-m}$ be independent generalized coordinate, $q_{n-m+1}, \dots, q_n$ dependent generalized coordinates (i.e., they can be expressed by $q_1, \dots, q_{n-m}$). Choose λ_i s.t.

$$\frac{\partial L}{\partial q_k} - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_k}\right) + \sum_{i=1}^{m}\lambda_i a_{ik} = 0 \tag{52}$$

$\forall k = n-m+1, \dots, n$. In conclusion, we have $q_1, \dots, q_n, \lambda_1, \dots, \lambda_m$ overall $n+m$ unknowns, and n Lagrange's equations and m constraint equations overall $n+m$ equations.

Remark.

1) It is inconvenient to reduce all q_ks to independent coordinates
2) If we are interested in the constraint forces

$$\sum_{k=1}^{n} a_{ik}\,\mathrm{d}q_k + a_{it}\,\mathrm{d}t = 0$$

where

$$a_{ik} = \frac{\partial f_i}{\partial q_k}, \quad a_{it} = \frac{\partial f_i}{\partial t}$$

Then

$$\mathrm{d}f_i = \frac{\partial f_i}{\partial q_k}\,\mathrm{d}q_k + \frac{\partial f_i}{\partial t}\,\mathrm{d}t \Rightarrow \mathrm{d}f_i = 0,\ f_i = \text{const}$$

Example 2.7 (Hoop rooling down an inclined plane)**.** Constraint equation

$$\dot{x} - r\dot{\theta} = 0 \Rightarrow x - r\theta = \text{const}$$

$a_x = 1$, $a_\theta = -r$, $a_t = 0$.
Energy terms are

$$\begin{aligned} T &= T_{\text{COM}} + T_{\text{relative}} = \frac{1}{2}M\dot{x}^2 + \frac{1}{2}M(r\dot{\theta})^2 \\ V &= Mg(l-x)\sin\phi \\ \Rightarrow L &= \frac{1}{2}M\dot{x}^2 + \frac{1}{2}M(r\dot{\theta})^2 - Mg(l-x)\sin\phi \end{aligned}$$

Then we can write the Lagrange's equation with Lagrange's multipliers

$$\begin{aligned} \frac{\partial L}{\partial x} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{x}} + a_x\lambda &= 0 \\ \Rightarrow Mg\sin\phi - M\ddot{x} + \lambda &= 0 \\ -Mr^2\ddot{\theta} - \lambda r &= 0 \\ \dot{x} = r\dot{\theta} &\Rightarrow \ddot{x} = r\ddot{\theta} \end{aligned}$$

we can get $M\ddot{x} = Mr\ddot{\theta} = -\lambda$ and $\ddot{x} = (g\sin\phi)/2$. Note that λ is the constraint force (in this case λ is the frictional force). check derivation