

Notes on Lagrangian Mechanics

Zisheng Ye

An n -dimensional coordinate space is used here. A vector in such a space is a set of numbers $\mathbf{x} = (x_1, \dots, x_n)$. Similarly, $\partial f / \partial \mathbf{x}$ means $(\partial f / \partial x_1, \dots, \partial f / \partial x_n)$, and $(\mathbf{a}, \mathbf{b}) = a_1 b_1 + \dots + a_n b_n$. $[\mathbf{a}, \mathbf{b}]$ is the outer product of \mathbf{a} and \mathbf{b} .

I. CALCULUS OF VARIATIONS

A functional refers to a linear mapping from a vector space V into its field of scalars.

A. Variations

Definition I.1. A functional Φ is called *differentiable* if $\Phi(\gamma + h) - \Phi(\gamma) = F + R$, where F depends linearly on h (for a fixed γ , $F(h_1 + h_2) = F(h_1) + F(h_2)$ and $F(ch) = cF(h)$), and $R(h, \gamma) = O(h^2)$ in the sense that, for $\|h\| < \varepsilon$ and $|dh/dt| < \varepsilon$, we have $|R| < C\varepsilon^2$. The linear part of the increment, $F(h)$, is called the *differential*.

It can be shown that if Φ is differentiable, its differential is *uniquely* define. The differential of a functional is also called its *variation*.

Theorem I.1. The functional $\Phi(\gamma) = \int_{t_0}^{t_1} L(x, \dot{x}, t) dt$ is differentiable, and its derivative is given by the formula

$$F(h) = \int_{t_0}^{t_1} \left[\frac{\partial L}{\partial x} - \frac{d}{dt} \frac{\partial L}{\partial \dot{x}} \right] h dt + \left(\frac{\partial L}{\partial \dot{x}} h \right) \Big|_{t_0}^{t_1}$$

Proof.

$$\begin{aligned} \Phi(\gamma + h) - \Phi(\gamma) &= \int_{t_0}^{t_1} [L(x + h, \dot{x} + \dot{h}, t) - L(x, \dot{x}, t)] dt \\ &= \int_{t_0}^{t_1} \left[\frac{\partial L}{\partial x} h + \frac{\partial L}{\partial \dot{x}} \dot{h} \right] dt + O(h^2) \\ &= F(h) + R \end{aligned}$$

where

$$\begin{aligned} F(h) &= \int_{t_0}^{t_1} \left[\frac{\partial L}{\partial x} h + \frac{\partial L}{\partial \dot{x}} \dot{h} \right] dt \\ &= \int_{t_0}^{t_1} \left[\frac{\partial L}{\partial x} - \frac{d}{dt} \frac{\partial L}{\partial \dot{x}} \right] h dt + \left(\frac{\partial L}{\partial \dot{x}} h \right) \Big|_{t_0}^{t_1} + O(h^2) \end{aligned}$$

and

$$R = O(h^2)$$

B. Extremals

Definition I.2. An extremal of a differentiable functional $\Phi(\gamma)$ is a curve γ such that $F(h) = 0$ for all h .

Theorem I.2. The curve $\gamma: x = x(t)$ is an extremal of the functional $\Phi(\gamma) = \int_{t_0}^{t_1} L(x, \dot{x}, t) dt$ on the space of curves passing through the points $x(t_0) = x_0$ and $x(t_1) = x_1$, if and only if

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) - \frac{\partial L}{\partial x} = 0$$

C. The Euler-Lagrange equation

Definition I.3. The equation

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) - \frac{\partial L}{\partial x} = 0$$

is called the *Euler-Lagrange equation* for the functional

$$\Phi = \int_{t_0}^{t_1} L(x, \dot{x}, t) dt$$

Theorem I.3 (Hamilton's form of the principle of least motion). The curve γ is an extremal of the functional $\Phi(\gamma) = \int_{t_0}^{t_1} L(\mathbf{x}, \dot{\mathbf{x}}, t) dt$ on the space of curves joining (t_0, \mathbf{x}_0) and (t_1, \mathbf{x}_1) , if and only if the Euler-Lagrange equation is satisfied along γ .

II. LAGRANGE'S EQUATIONS

Theorem II.1. Motions of the mechanical system from Newton's equations of dynamics coincide with extremal of the functional

$$\Phi(\gamma) = \int_{t_0}^{t_1} L dt, \quad L = T - U$$

is the difference between the kinetic and potential energy.

Proof. $U = U(\mathbf{r})$ and $T = \sum m_i \dot{r}_i^2 / 2$, we have $\partial L / \partial \dot{r}_i = \partial T / \partial \dot{r}_i = m_i \dot{r}_i$ and $\partial L = \partial r_i = -\partial U / \partial r_i$. This leads to

$$\frac{d}{dt} (m_i \dot{r}_i) + \frac{\partial U}{\partial r_i} = 0$$

□

Corollary 1. Let (q_1, \dots, q_{3n}) be any coordinates in the configuration space of a system of n mass points. Then the evolution of \mathbf{q} with time is subject to the Euler-Lagrange equations

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\mathbf{q}}} \right) - \frac{\partial L}{\partial \mathbf{q}} = 0, \quad \text{where } L = T - U$$

Definition II.1. $L(\mathbf{q}, \dot{\mathbf{q}}, t) = T - U$ is the Lagrange function or Lagrangian. q_i are the generalized coordinates. \dot{q}_i are

□

generalized velocities. $\frac{\partial L}{\partial \dot{q}_i} = p_i$ are generalized momenta. $\frac{\partial L}{\partial q_i}$ are generalized forces. $\int_{t_0}^{t_1} L(\mathbf{q}, \dot{\mathbf{q}}, t) dt$ is the action. $\frac{d}{dt}(m_i \dot{r}_i) + \frac{\partial U}{\partial r_i} = 0$ are Lagrange's equations.

A. Examples

Example 1. For a free mass point in E^3 ,

$$L = T = \frac{m\dot{\mathbf{r}}^2}{2}$$

in cartesian coordinates $q_i = r_i$ we find

$$L = \frac{m}{2}(\dot{q}_1^2 + \dot{q}_2^2 + \dot{q}_3^2)$$

Here the generalized velocities are the components of the velocity vector, the generalized momenta $p_i = m\dot{q}_i$ are the components of the momentum vector, and Lagrange's equations coincide with Newton's equations $\frac{d\mathbf{p}}{dt} = 0$. The extremals are straight lines. It follows from Hamilton's principle that straight lines are not only shortest but also extremals of the action $\int_{t_0}^{t_1} (\dot{q}_1^2 + \dot{q}_2^2 + \dot{q}_3^2) dt$.

Example 2. Consider planar motion in a central field in polar coordinates $q_1 = r, q_2 = \varphi$. From the relation $\dot{\mathbf{r}} = \dot{r}\mathbf{e}_r + \dot{\varphi}\mathbf{e}_\varphi$, the kinetic energy is $T = \frac{1}{2}m\dot{\mathbf{r}}^2 = \frac{1}{2}m(\dot{r}^2 + r^2\dot{\varphi}^2)$ and the lagrangian $L(\mathbf{q}, \dot{\mathbf{q}}) = T(\mathbf{q}, \dot{\mathbf{q}}) - U(\mathbf{q})$, where $U = U(q_1)$.

The generalized momenta will be $\mathbf{p} = \partial L / \partial \dot{\mathbf{q}}$

$$p_1 = m\dot{r}, \quad p_2 = mr^2\dot{\varphi}$$

The first Lagrange equation $\dot{p}_1 = \partial L / \partial q_1$ takes the form

$$m\ddot{r} = mr\dot{\varphi}^2 - \frac{\partial U}{\partial r}$$

Since $q_2 = \varphi$ does not enter into L , we have $\partial L / \partial q_1 = 0$. Therefore, the second Lagrange equation will be $\dot{p}_2 = 0, p_2 = \text{const.}$ This is the law of conservation of angular momentum.

Definition II.2. A coordinate q_i is called *cyclic* if it does not enter into the lagrangian: $\partial L / \partial q_i = 0$.

Theorem II.2. The generalized momentum corresponding to a cyclic coordinate is conserved: $p_i = \text{const.}$

III. LEGENDRE TRANSFORMATIONS

The Legendre transformation transforms functions on a vector space to functions on the dual space. Legendre transformations are related to projective duality and tangential coordinates in algebraic geometry and the construction of dual Banach spaces in analysis.

A. Definition

Let $y = f(x)$ be a convex function, $f''(x) > 0$. For each p the function $px - f(x) = F(p, x)$ has a maximum with respect to x at the point $x(p)$. Then define $g(p) = F(p, x(p))$. The point $x(p)$ is defined by the extremal condition $\partial F / \partial x = 0$. Since f is convex, the point $x(p)$ is unique.

B. Involutivity

Theorem III.1. The Legendre transformation is involutive, its square is the identity: if under the Legendre transformation f is taken to g , then the Legendre transform of g will again be f .

IV. HAMILTON'S EQUATIONS

By means of a Legendre transformation, a lagrangian system of second-order differential equations is converted into a remarkably symmetrical system of $2n$ first-order equations called a hamiltonian system of equations (or canonical equations).

A. Equivalence of Lagrange's and Hamilton's equations

Consider the system of Lagrange's equations $\dot{\mathbf{p}} = \partial L / \partial \dot{\mathbf{q}}$, where $\mathbf{p} = \partial L / \partial \dot{\mathbf{q}}$, with a given lagrangian function $L : \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}$, which we will assume to be convex with respect to the second argument $\dot{\mathbf{q}}$.

Theorem IV.1. The system of Lagrange's equations is equivalent to the system of $2n$ first-order equations (Hamilton's equations)

$$\begin{aligned} \dot{\mathbf{p}} &= - \frac{\partial H}{\partial \mathbf{q}} \\ \dot{\mathbf{q}} &= \frac{\partial H}{\partial \mathbf{p}} \end{aligned}$$

where $H(\mathbf{p}, \mathbf{q}, t) = \mathbf{p}\dot{\mathbf{q}} - L(\mathbf{q}, \dot{\mathbf{q}}, t)$ is the Legendre transform of the lagrangian function viewed as a function of $\dot{\mathbf{q}}$.

Proof. The Legendre transform of $L(\mathbf{q}, \dot{\mathbf{q}}, t)$ with respect to $\dot{\mathbf{q}}$ is the function $H(\mathbf{q}) = \mathbf{p}\dot{\mathbf{q}} - L(\dot{\mathbf{q}})$, in which $\dot{\mathbf{q}}$ is expressed in terms of \mathbf{p} by the formula $\mathbf{p} = \partial L / \partial \dot{\mathbf{q}}$, and which depends on the parameters \mathbf{q} and t . This function H is called the *hamiltonian*.

The total differential of the hamiltonian

$$dH = \frac{\partial H}{\partial \mathbf{p}} d\mathbf{p} + \frac{\partial H}{\partial \mathbf{q}} d\mathbf{q} + \frac{\partial H}{\partial t} dt$$

is equal to the total differential of $\mathbf{p}\dot{\mathbf{q}} - L$ for $\mathbf{p} = \partial L / \partial \dot{\mathbf{q}}$:

$$dH = \dot{\mathbf{q}} d\mathbf{p} - \frac{\partial L}{\partial \mathbf{q}} d\mathbf{q} - \frac{\partial L}{\partial t} dt$$

Both expressions for dH must be the same. Therefore,

$$\dot{\mathbf{q}} = \frac{\partial H}{\partial \mathbf{p}}, \quad \frac{\partial H}{\partial \mathbf{q}} = - \frac{\partial L}{\partial \mathbf{q}}, \quad \frac{\partial H}{\partial t} = - \frac{\partial L}{\partial t}$$

Applying Lagrange's equations $\dot{\mathbf{p}} = \partial L / \partial \dot{\mathbf{q}}$, we obtain Hamilton's equations. \square

B. Hamilton's function and energy

Lemma IV.1. The values of a quadratic form $f(\mathbf{x})$ and of its Legendre transform $g(\mathbf{p})$ coincide at corresponding points: $f(\mathbf{x}) = g(\mathbf{p})$.

Proof. By Euler's theorem on homogeneous function

$$\frac{\partial f}{\partial \mathbf{x}} \mathbf{x} = 2f(\mathbf{x})$$

Therefore

$$g(\mathbf{p}(\mathbf{x})) = \mathbf{p}\mathbf{x} - f(\mathbf{x}) = \frac{\partial f}{\partial \mathbf{x}}\mathbf{x} - f(\mathbf{x}) = f(\mathbf{x})$$

□

Theorem IV.2. The hamiltonian H is the total energy $H = T + U$.

Proof. Reasoning as in the lemma,

$$H = \mathbf{p}\dot{\mathbf{q}} - L = 2T - (T - U) = T + U$$

□

Corollary 2. $dH/dt = \partial H/\partial t$. In particular, for a system whose hamiltonian function does not depend explicitly on time ($\partial H/\partial t = 0$), the law of conservation of the hamiltonian function holds: $H(\mathbf{p}(t), \mathbf{q}(t)) = \text{const.}$

Proof. By Hamilton's equations

$$\frac{dH}{dt} = \frac{\partial H}{\partial \mathbf{p}} \left(-\frac{\partial H}{\partial \mathbf{q}} \right) + \frac{\partial H}{\partial \mathbf{q}} \frac{\partial H}{\partial \mathbf{p}} + \frac{\partial H}{\partial t} = \frac{\partial H}{\partial t}$$

□

C. Cyclic coordiantes

Definition IV.1. If a coordinate q_i does not enter into the hamiltonian function H , $\partial H/\partial q_i = 0$, then it is called cyclic (the term comes from the particular case of the angular coordinate in a central field).

The coordinate q_1 is cyclic if and only if it does not enter into the lagrangian function ($\partial L/\partial q_1 = 0$). It follows from the hamiltonian form of the equations of motion that:

Corollary 3. Let q_1 be a cyclic coordinate. Then p_1 is a first integral. In this case the variation of the remaining coordinates with time is the same as in a system with the $n-1$ independent coordinates q_2, \dots, q_n and with hamiltonian function

$$H(p_2, \dots, p_n; q_2, \dots, q_n; t, c)$$

depending on the parameter $c = p_1$.

Proof. Set $\mathbf{p}' = (p_2, \dots, p_n)$ and $\mathbf{q}' = (q_2, \dots, q_n)$. Then Hamilton's equations take the form

$$\begin{aligned} \frac{d}{dt}\mathbf{q}' &= \frac{\partial H}{\partial \mathbf{p}'} & \frac{d}{dt}q_1 &= \frac{\partial H}{\partial p_1} \\ \frac{d}{dt}\mathbf{p}' &= -\frac{\partial H}{\partial \mathbf{q}'} & \frac{d}{dt}p_1 &= 0 \end{aligned}$$

The last equation show that $p_1 = \text{const.}$ Therefore, in the system of equations for \mathbf{p}' and \mathbf{q}' , the value of p_1 enters only as a parameter in the hamiltonian function. After this system of $2n-2$ equations is solved, the equation for q_1 takes the form

$$\frac{d}{dt}q_1 = f(t), \text{ where } f(t) = \frac{\partial}{\partial p_1} H(p_1, \mathbf{p}'(t), \mathbf{q}'(t), t)$$

and is easily integrated. □

Almost all the solved problems in mechancis have been solved by means of the above corollary.

V. LIOUVILLE'S THEOREM

The phase flow of Hamilton's equations preserves phase volume. It follows atth a hamiltonian system cannot be asymptotically stable. Here suppose the hamiltonian function does not depend explicitly on the time: $H = H(\mathbf{p}, \mathbf{q})$.

Definition V.1. The $2n$ -dimensional space with coordinates $p_1, \dots, p_n; q_1, \dots, q_n$ is called phase space.

Definition V.2. The phase flow is the one-parameter group of transformation of phase space

$$g^t : (\mathbf{p}(0), \mathbf{q}(0)) \mapsto (\mathbf{p}(t), \mathbf{q}(t))$$

where $\mathbf{p}(t)$ and $\mathbf{q}(t)$ are solutions of hamiltonian's system of equations.

A. Liouville's theorem

Suppose given a system of ordinary differential equations $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x})$, whose solution may be extended to the whole time axis. Let $\{g^t\}$ be the corresponding group of transformation:

$$g^t(\mathbf{x}) = \mathbf{x} + \mathbf{f}(\mathbf{x})t + O(t^2), \quad (t \mapsto 0).$$

Let $D(0)$ be a region in \mathbf{x} -space and $v(0)$ its volume;

$$v(t) = \text{volume of } D(t) \quad D(t) = g^t D(0)$$

Lemma V.1. For any matrix $A = (a_{ij})$

$$\det(I + At) = 1 + t \text{tr} A + O(t^2)$$

where I is the identity matrix and $\text{tr} A = \sum_{i=1}^n a_{ii}$ is the trace of A .

Proof. By direct expansion of the determinant

$$\begin{aligned} \det(I + At) &= \sum_{k=0}^{\infty} \frac{1}{k!} \left(-\sum_{j=1}^{\infty} \frac{(-1)^j t^j}{j} \text{tr}(A^j) \right)^k \\ &= 1 + t \text{tr} A - \sum_{j=2}^{\infty} \frac{(-1)^j t^j}{j} \text{tr}(A^j) \\ &\quad + \sum_{k=2}^{\infty} \frac{1}{k!} \left(-\sum_{j=1}^{\infty} \frac{(-1)^j t^j}{j} \text{tr}(A^j) \right)^k \\ &= 1 + t \text{tr} A + O(t^2) \end{aligned}$$

□

Lemma V.2. $(dv/dt)|_{t=0} = \int_{D(0)} \text{div} \mathbf{f} d\mathbf{x}$

Proof.

$$\begin{aligned} v(t) &= \int_{D(0)} \det \frac{\partial g^t(\mathbf{x})}{\partial \mathbf{x}} d\mathbf{x} \\ &= \int_{D(0)} \det \left(I + \frac{\partial \mathbf{f}}{\partial \mathbf{x}} t + O(t^2) \right) d\mathbf{x} \\ &= \int_{D(0)} \left(1 + t \text{tr} \frac{\partial \mathbf{f}}{\partial \mathbf{x}} + O(t^2) \right) d\mathbf{x} \\ &= \int_{D(0)} \left(1 + t \sum_{i=1}^n \frac{\partial f_i}{\partial x_i} + O(t^2) \right) d\mathbf{x} \end{aligned}$$

$$= \int_{D(0)} (1 + t \operatorname{div} \mathbf{f} + O(t^2)) \, d\mathbf{x}$$

which directly proves the lemma. \square

Theorem V.1. *If $\operatorname{div} \mathbf{f} \equiv 0$, then g^t preserves volume: $v(t) = v(0)$.*

Proof. From the lemma above, for any time t_0

$$\left. \frac{dv(t)}{dt} \right|_{t=t_0} = \int_{D(t_0)} \operatorname{div} \mathbf{f} \, d\mathbf{x}$$

and if $\operatorname{div} \mathbf{f} \equiv 0$, $dv/dt = 0$. \square

Theorem V.2 (Liouville's theorem). *The phase flow preserves volume: for any region D*

$$\text{volume of } g^t D = \text{volume of } D$$

Proof. In particular, for hamilton's equations we have

$$\operatorname{div} \mathbf{f} = \frac{\partial}{\partial \mathbf{p}} \left(-\frac{\partial H}{\partial \mathbf{q}} \right) + \frac{\partial}{\partial \mathbf{q}} \left(\frac{\partial H}{\partial \mathbf{p}} \right) \equiv 0$$

which proves Liouville's theorem. \square

B. Poincaré's recurrence theorem

Liouville's theorem allows one to apply methods of *ergodic theory* to the study of mechanics. Here is the simplest example.

Theorem V.3 (Poincaré's theorem). *Let g be a volume-preserving continuous one-to-one mapping which maps a bounded region D of euclidean space onto itself: $gD = D$. Then in any neighborhood U of any point of D there is a point $x \in U$ which returns to U , $g^n x \in U$ for some $n > 0$.*

Proof. Consider the images of the neighborhood U

$$U, gU, g^2U, \dots, g^nU, \dots$$

All of these have the same volume. If they never intersected, D would have infinite volume. Therefore, for some $k \geq 0$ and $l \geq 0$, with $k > l$,

$$g^k U \cap g^l U \neq \emptyset$$

Therefore, $g^{k-l} \cap gU \neq \emptyset$. If y is in this intersection, then $y = g^n x$, with $x \in U$ ($n = k - l$). Then $x \in U$ and $g^n x \in U$ ($n = k - l$). \square

This theorem applies, for example, to the phase flow g^t of a two-dimensional system whose potential $U(x_1, x_2)$ goes to infinity as $(x_1, x_2) \rightarrow \infty$; in this case the invariant bounded region in phase space is given by the condition

$$D = \{\mathbf{p}, \mathbf{q} : T + U \leq E\}$$

Poincaré's theorem can be strengthened, showing that almost every moving point returns repeatedly to the vicinity of its initial position. This is one of the few general conclusions which can be drawn about the character of motion.

If you open a partition separating a chamber containing gas and a chamber with a vacuum, then after a while the gas molecules will again collect in the first chamber. The

resolution of the paradox lies in the fact that "a while" may be longer than the duration of the solar system's existence.

Example 3. Let D be a circle and g rotation through an angle α . If $\alpha = 2\pi(m/n)$, then g^n is the identity, and the theorem is obvious. If α is not commensurable with 2π , then Poincaré's theorem gives

$$\forall \delta > 0, \exists n : |g^n x - x| < \delta$$

Example 4. Let D be the two-dimensional torus and φ_1 and φ_2 angular coordinates on it (longitude and latitude). Consider the system of ordinary differentiable equations on the torus

$$\dot{\varphi}_1 = \alpha_1 \quad \dot{\varphi}_2 = \alpha_2$$

Clearly, $\operatorname{div} \mathbf{f} = 0$ and the corresponding motion

$$g^t : (\varphi_1, \varphi_2) \rightarrow (\varphi_1 + \alpha_1 t, \varphi_2 + \alpha_2 t)$$

preserves the volume $d\varphi_1 d\varphi_2$. From Poincaré's theorem it is easy to deduce.

Finally, this kind of deduction could be extended into any n -dimensional torus given by n angular coordinates.

VI. HOLONOMIC CONSTRAINTS

Let γ be a smooth curve in the plane. If there is a very strong force field in a neighborhood of γ , directed towards the curve, then a moving point will always be close to γ . In the limit case of an infinite force field, the point must remain on the curve γ . In this case we say that a constraint is put on the system.

Definition VI.1. Let γ be an m -dimensional surface in the $3n$ -dimensional configuration space of the points $\mathbf{r}_1, \dots, \mathbf{r}_n$ with masses m_1, \dots, m_n . Let $\mathbf{q} = (q_1, \dots, q_m)$ be some coordinates on γ : $\mathbf{r}_i = \mathbf{r}_i(\mathbf{q})$. The described by the equations

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{q}}} = \frac{\partial L}{\partial \mathbf{q}}, \quad L = \frac{1}{2} \sum m_i \dot{\mathbf{r}}_i^2 + U(\mathbf{q})$$

is called a system of n points with $3n - m$ ideal *holonomic constraints*. The surface γ is called the *configuration space of the system with constraints*. If the surface γ is given by $k = 3n - m$ functionally independent equations $f_1(\mathbf{r}) = 0, \dots, f_k(\mathbf{r}) = 0$, then we say that the system is constrained by the relations $f_1 = 0, \dots, f_k = 0$.

Holonomic constraints also could have been defined as the limiting case of a system with a large potential energy. The meaning of these constraints in mechanics lies in the experimentally determined fact that many mechanical systems belong to this class more or less exactly.

VII. DIFFERENTIABLE MANIFOLDS

A. Definition of differentiable manifold

The configuration space of a system with constraints is a differentiable manifold. A set M is given the structure of a differentiable manifold if M is provided with a finite or countable collection of *charts*, so that every point is represented in at least one chart. A chart is an open set U in the euclidean

coordinate space $\mathbf{q} = (q_1, \dots, q_n)$, together with a one-to-one mapping φ of U onto some subset of M , $\varphi : U \rightarrow \varphi U \subset M$. We assume that if points \mathbf{p} and \mathbf{p}' in two charts U and U' have the same image in M , then \mathbf{p} and \mathbf{p}' have neighborhoods $V \subset U$ and $V' \subset U'$ with the same image in M . In this way we get a mapping $\varphi'^{-1}\varphi : V \rightarrow V'$. This is a mapping of the region V of the euclidean space \mathbf{q} onto the region V' of the euclidean space \mathbf{q}' , and it is given by n functions of n variables, $\mathbf{q}' = \mathbf{q}'(\mathbf{q})$, $(\mathbf{q}) = \mathbf{q}(\mathbf{q}')$. The charts U and U' are called *compatible* if these functions are differentiable. An *atlas* is a union of compatible charts. Two atlases are *equivalent* if their union is also an atlas. A differentiable manifold is a class of equivalent atlases. We will consider only *connected* manifolds. Then the number n will be the same for all charts; it is called the *dimension* of the manifold. A *neighborhood* of a point on a manifold is the image under a mapping $\varphi : U \rightarrow M$ of a neighborhood of the representation of this point in a chart U . We will assume that every two different points have non-intersecting neighborhoods.

Definition VII.1. The dimension of the configuration space is called the *number of degrees of freedom*.

B. Tangent space

If M is a k -dimensional manifold embedded in E^n , then at every point \mathbf{x} we have a k -dimensional tangent space $TM_{\mathbf{x}}$. Namely, $TM_{\mathbf{x}}$ is the orthogonal complement to $\{\text{grad}f_1, \dots, \text{grad}f_{n-k}\}$. The vectors of the tangent space $TM_{\mathbf{x}}$ based at \mathbf{x} are called tangent vectors to M at \mathbf{x} . We can also define these vectors directly as velocity vectors of curves in M :

$$\dot{\mathbf{x}} = \lim_{t \rightarrow 0} \frac{\varphi(t) - \varphi(0)}{t} \quad \text{where } \varphi(0) = \mathbf{x}, \varphi(t) \in M$$

The definition of tangent vectors can also be given in the intrinsic terms, independent of the embedding of M into E^n . We will call two curves $\mathbf{x} = \varphi(t)$ and $\mathbf{x} = \psi(t)$ equivalent if $\varphi(0) = \psi(0) = \mathbf{x}$ and $\lim_{t \rightarrow 0} (\varphi(t) - \psi(t))/t = 0$ in some charts. Then this tangent relationship is true in any chart.

Definition VII.2. A tangent vector to a manifold M at the point \mathbf{x} is an equivalence class of curves $\varphi(t)$, with $\varphi(0) = \mathbf{x}$.

It is easy to define the operations of multiplication of a tangent vector by a number and addition of tangent vectors. The set of tangent vectors to M at \mathbf{x} forms a *vector space* $TM_{\mathbf{x}}$. This space is also called the *tangent space* to M at \mathbf{x} .

Definition VII.3. Let U be a chart of an atlas for M with coordinates q_1, \dots, q_n . Then the *components* of the tangent vector of the curve $\mathbf{q} = \varphi(t)$ are the numbers ξ_1, \dots, ξ_n , where $\xi_i = (d\varphi_i/dt)|_{t=0}$.

C. Tangent bundle

The union of the tangent spaces to M at the various points, $\bigcup_{\mathbf{x} \in M} TM_{\mathbf{x}}$, has a natural differentiable manifold structure, the dimension of which is twice the dimension of M . The manifold is called the *tangent bundle* of M and is denoted by TM . A point of TM is a vector ξ , tangent to M at some

point \mathbf{x} . Local coordinates on TM are constructed as follows. Let q_1, \dots, q_n be local coordinates on M , and ξ_1, \dots, ξ_n components of a tangent vector in this coordinates system. Then the $2n$ numbers $(q_1, \dots, q_n, \xi_1, \dots, \xi_n)$ give a local coordinate system on TM . One sometimes writes dq_i for ξ_i . The mapping $p : TM \rightarrow M$ which takes a tangent vector ξ to the point $\mathbf{x} \in M$ at which the vector is tangent to M ($\xi \in TM_{\mathbf{x}}$), is called the *natural projection*. The inverse image of a point $\mathbf{x} \in M$ under the natural projection, $p^{-1}(\mathbf{x})$, is the tangent space $TM_{\mathbf{x}}$. This space is called the *fiber of the tangent bundle over the point \mathbf{x}* .

D. Riemannian manifolds

If M is a manifold embedded in euclidean space, then the metric on euclidean space allows us to measure the lengths of curves, angles between vectors, volumes, etc. All of these quantities are expressed by means of the lengths of tangent vectors, that is, by the positive-definite quadratic form given on every tangent space $TM_{\mathbf{x}}$:

$$TM_{\mathbf{x}} \rightarrow \mathbb{R} \quad \xi \rightarrow \langle \xi, \xi \rangle$$

Definition VII.4. A differentiable manifold with a fixed positive-definite quadratic form $\langle \xi, \xi \rangle$ on every tangent space $TM_{\mathbf{x}}$ is called a *Riemannian manifold*. The quadratic form is called the *Riemannian metric*.

Let U be a chart of an atlas for M with coordinates q_1, \dots, q_n . Then a Riemannian matrix is given by the formula

$$ds^2 = \sum_{i,j=1}^n a_{ij}(\mathbf{q}) dq_i dq_j \quad a_{ij} = a_{ji}$$

where dq_i are the coordinates of a tangent vector.

E. The derivative map

Let $f : M \rightarrow N$ be a mapping of a manifold M to a manifold N . f is called differentiable if in local coordinates on M and N it is given by differentiable functions.

Definition VII.5. The *derivative* of a differentiable mapping $f : M \rightarrow N$ at a point $\mathbf{x} \in M$ is the linear map of the tangent spaces

$$f_{*\mathbf{x}} : TM_{\mathbf{x}} \rightarrow TN_{f(\mathbf{x})}$$

which is given in the following way:

Let $\mathbf{v} \in TM_{\mathbf{x}}$. Consider a curve $\varphi : \mathbb{R} \rightarrow M$ with $\varphi(0) = \mathbf{x}$, and velocity vector $d\varphi/dt|_{t=0} = \mathbf{v}$. Then $f_{*\mathbf{x}}\mathbf{v}$ is the velocity vector of the curve $f \circ \varphi : \mathbb{R} \rightarrow N$,

$$f_{*\mathbf{x}}\mathbf{v} = \left. \frac{d}{dt} \right|_{t=0} f(\varphi(t))$$

VIII. LAGRANGIAN DYNAMICAL SYSTEMS

A. Definition of a lagrangian system

Let M be a differentiable manifold, TM its tangent bundle, and $L : TM \rightarrow \mathbb{R}$ a differentiable function. A map $\gamma : \mathbb{R} \rightarrow M$ is called a *motion in the lagrangian system with*

configuration manifold M and lagrangian function L if γ is an extremal of the functional

$$\Phi(\gamma) = \int_{t_0}^{t_1} L(\dot{\gamma}) dt$$

where $\dot{\gamma}$ is the velocity vector $\dot{\gamma}(t) \in TM_{\gamma(t)}$.

Theorem VIII.1. *The evolution of the local coordinates $\mathbf{q} = (q_1, \dots, q_n)$ of a point $\gamma(t)$ under motion in a lagrangian system on a manifold satisfies the Lagrange equations*

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\mathbf{q}}} = \frac{\partial L}{\partial \mathbf{q}}$$

where $L(\mathbf{q}, \dot{\mathbf{q}})$ is the expression for the function $L : TM \rightarrow \mathbb{R}$ in the coordinates \mathbf{q} and $\dot{\mathbf{q}}$ on TM .

Let M be a Riemannian manifold. The quadratic form on each tangent space,

$$T = \frac{1}{2} \langle \mathbf{v}, \mathbf{v} \rangle \quad \mathbf{v} \in TM_{\mathbf{x}}$$

is called the *kinetic energy*. A differentiable function $U : M \rightarrow \mathbb{R}$ is called a *potential energy*.

Definition VIII.1. A lagrangian system on a Riemannian manifold is called *natural* if the lagrangian function is equal to the difference between kinetic and potential energies: $L = T - U$.

B. Systems with holonomic constraints

Consider the configuration manifold M of a system with constraint as embedded in the $3n$ -dimensional configuration space of a system of free points. The metric on the $3n$ -dimensional space is given by the quadratic form $\sum_{i=1}^n m_i \dot{\mathbf{r}}_i^2$. The embedded Riemannian manifold M with potential energy U coincides with the system defined previously or with limiting case of the system with potential $U + N\mathbf{q}_2^2$, $N \rightarrow \infty$, which grows rapidly outside of M .

C. Procedure for solving problems with constraints

- 1) Determine the configuration manifold and introduce coordinates q_1, \dots, q_n (in a neighborhood of each of its points).
- 2) Express the kinetic energy $T = \sum \frac{1}{2} m_i \dot{\mathbf{r}}_i^2$ as a quadratic form in the generalized velocities

$$T = \frac{1}{2} \sum a_{ij}(\mathbf{q}) \dot{q}_i \dot{q}_j$$

- 3) Construct the lagrangian function $L = T - U(\mathbf{q})$ and solve Lagrange's equations.

Example 5. Consider the motion of a point mass of mass 1 on a surface of revolution in three-dimensional space. It can be shown that the orbits are geodesics on the surface. In cylindrical coordinates r, φ, z the surface is given (locally) in the form $r = r(z)$ or $z = z(r)$. The kinetic energy has the form

$$T = \frac{1}{2} (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) = \frac{1}{2} [(1 + \dot{r}_z^2) \dot{z}^2 + r^2(z) \dot{\varphi}^2]$$

in coordinates φ and z , and

$$T = \frac{1}{2} (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) = \frac{1}{2} [(1 + \dot{r}_z^2) \dot{z}^2 + r^2(z) \dot{\varphi}^2]$$

in coordinates r and φ . (Note: $\dot{x}^2 + \dot{y}^2 = \dot{r}^2 + r^2 \dot{\varphi}^2$)

The lagrangian function L is equal to T . In both coordinates systems φ is a cyclic coordinate. The corresponding momentum is preserved: $p_\varphi = r^2 \dot{\varphi}$ is nothing other than the z -component of angular momentum. Since the system has two degrees of freedom, knowing the cyclic coordinate φ is sufficient for integrating the problem completely. Denote by α the angle of the orbit with a meridian. We have $r \dot{\varphi} = |v| \sin \alpha$, where $|v|$ is the magnitude of the velocity vector. By the law of conservation of energy, $H = L = T$ is preserved. Therefore, $|v|$ is constant. So the conservation law for p_φ takes the form $r \sin \alpha = \text{const}$. This relationship shows that this motion takes place in the region $|\sin \alpha| \leq 1$. Furthermore, the inclination of the orbit from the meridian increases as the radius r decreases. When the radius reaches the smallest possible value, $r = r_0 \sin \alpha_0$, the orbit is reflected and returns to the region with larger r .

D. Non-autonomous systems

A *lagrangian non-autonomous system* differs from the autonomous systems by the additional dependence of the lagrangian function on time:

$$L : TM \times \mathbb{R} \rightarrow \mathbb{R} \quad L = L(\mathbf{q}, \dot{\mathbf{q}}, t)$$

In particular, both the kinetic and potential energies can depend on time in a non-autonomous natural system:

$$T : TM \times \mathbb{R} \rightarrow \mathbb{R} \quad T = T(\mathbf{q}, \dot{\mathbf{q}}, t)$$

$$U : M \times \mathbb{R} \rightarrow \mathbb{R} \quad U = U(\mathbf{q}, t)$$

A system of n mass points, constrained by holonomic constraints dependent on time, is defined with the help of a time-dependent submanifold of the configuration space of a free system. Such a manifold is given by a mapping

$$i : M \times \mathbb{R} \rightarrow E^{3n} \quad i(\mathbf{q}, t) = \mathbf{x}$$

which, for any fixed $t \in \mathbb{R}$, defines an embedding $M \rightarrow E^{3n}$.

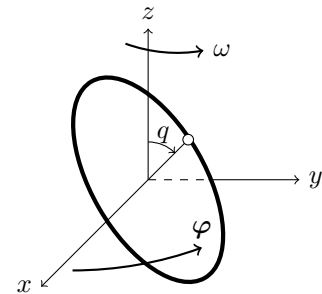


Fig. 1. Bead on a rotating circle

Example 6. Consider the motion of a bead along a vertical circle of radius r (Fig. 1) which rotates with angular velocity

ω around the vertical axis passing through the center O of the circle. The manifold M is the circle. Let q be the angular coordinate on the circle, measured from the highest point. Let x, y , and z be cartesian coordinates in E^3 with origin O and vertical axis z . Let φ be the angle of the plane of the circle with the plane xOz . By hypothesis, $\varphi = \omega t$. The mapping $i : M \times \mathbb{R} \rightarrow E^3$ is given by the formula

$$i(q, t) = (r \sin q \cos \omega t, r \sin q \sin \omega t, r \cos q)$$

From this formula,

$$T = \frac{m}{2}(\omega^2 r^2 \sin^2 q + r^2 \dot{q}^2), \quad U = mgr \cos q$$

In this case the lagrangian function $L = T - U$ turns out to be independent of t , although the constrain does depend on time. Furthermore, the lagrangian function turns out to be the same as in the one-dimensional system with kinetic energy.