

## Brief Mechanics

### Notes from Physics 311

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work in progress...

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content

#### 1 Equation of Motion:

##### Lagrangian, Principle of Least Action, and E-L Equation

###### 1.1 Lagrangian:

- Under the constraint of  
1) Space and time are homogeneous, 2) time is isotropic, the  
Lagrangian for a system is given as

$$L = T - U(r), \text{ where } \begin{cases} T = \sum_{a=1}^N \frac{1}{2} m_a \dot{q}_a^2 & \text{sum of KE} \\ U: & \text{potential energy} \end{cases} \quad (1)$$

###### 1.2 E-L equation

For a given functional,

$$S = \int_{t_1}^{t_2} L(q, \dot{q}, t) dt \quad (2)$$

we could optimize it using the Euler-Lagrange equation,

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = 0 \quad (3)$$

where each EL equation and its solution corresponds to a degree of freedom.

Upon applying the EL equation to a generalized Lagrangian, we reveal Newton's second law

$$\begin{aligned} \frac{d}{dt} \frac{\partial (\frac{1}{2} m v^2 - U(r))}{\partial v} &= \frac{\partial (\frac{1}{2} m \dot{q}^2 - U(r))}{\partial r} \\ \Rightarrow m \ddot{v} &= - \frac{\partial U}{\partial q} \equiv \vec{F}(\text{force}) \end{aligned} \quad (4)$$

###### 1.3 coordinate transformation:

- In cartesian coordinates,  $L = \frac{1}{2} m (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - U$   
In cylindrical coordinates,  $L = \frac{1}{2} m (\dot{r}^2 + r^2 \dot{\theta}^2 + \dot{z}^2) - U$   
In spherical coordinates,  $L = \frac{1}{2} m (\dot{r}^2 + r^2 \dot{\theta}^2 + r^2 \sin^2(\theta) \dot{\phi}^2) - U$
  - Note that when taking partial differentiations, we treat each variable and its derivative as two independent variables. Don't ask why... We are doing physics here
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#### 2 Conservation Laws:

##### Energy, Momentum, COM, and Angular Momentum

## 2.1 Energy:

- Energy is defined as the following, and when the Lagrangian is **homogeneity time**, the energy is conserved.

$$E \equiv \sum_i \dot{q}_i \frac{\partial L}{\partial \dot{q}_i} - L \quad (5)$$

considering  $L = T - U$ , we have  $\boxed{E = T + U}$

- Total energy is also given as

$$E = \frac{1}{2} \mu V^2 + E_i \quad (6)$$

where  $E_i$  is internal energy, and  $\mu$  being the total mass

## 2.2 General momentum:

conservation of general momentum is from the following conservation

$$\frac{\partial L}{\partial q_j} = 0 \Rightarrow p_j \equiv \frac{\partial L}{\partial \dot{q}_j}, \quad (7)$$

where  $q_j$  is a cyclic coordinate, i.e.  $L$  is independent of  $q_j$ .

## 2.3 Total momentum

total momentum is defined as the following, and considering the **homogeneity of space**, the momentum is conserved in a closed system.

If the total momentum of a mechanical system in a given frame of reference is 0, then the said system is at rest relative to that frame. For simplicity's sake, we want to choose our frame of reference in which the total momentum is zero.

$$P \equiv \sum_a \frac{\partial L}{\partial \dot{q}_a} = \boxed{\sum_a m_a v_a} \quad (8)$$

force is also given by  $F_j = \frac{\partial L}{\partial q_j}$

sum of all forces in a closed system is 0

## 2.4 Center of Mass

- Center of mass is defined so that, the velocity of the system as a whole,  $V = P/(\sum m_a)$  is the time derivative of the center of mass.  $R = \sum_a m_a r_a / (\sum m_a)$ .

## 2.5 Conservation of angular momentum

Angular momentum characterizes the rotation of the system, and considering the **isotropy of space**, the angular momentum is conserved in a closed system.

$$\boxed{\vec{L} \equiv \sum_a r_a \times p_a} \text{ is conserved in a closed system} \quad (9)$$

- Angular momentum can be found by differentiating the lagrangian with respect to angular velocity, along the rotation axis z:

$$\vec{L}_z = \frac{\partial L}{\partial \dot{\varphi}_a} \quad (10)$$

### 3 Integration of the equations of motion: Connetcting Energy with motion

#### 3.1 Motion in 1 dimension

- For a system with DOF=1, and with  $\frac{\partial L}{\partial t} = 0$  (largrangian independent of time, i.e. energy conserved) , we can write the largrangian and total energy as

$$L = \frac{1}{2}m\dot{x}^2 - U(x), \quad (11)$$

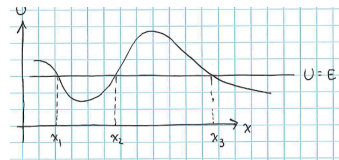
$$E = \frac{1}{2}m\dot{x}^2 + U(x) \quad (12)$$

Equation 12 is a differential equation of position and time. Solving this ODE for time gives:

$$t = \sqrt{\frac{m}{2}} \int \frac{dx}{E - U(x)} + C \quad (13)$$

when given  $U(x)$ , and by plugging it into Equation 12, we can solve for  $x(t)$  by substitution. Tricks on sub: when  $U(x)$  is of order 1, use u-sub; when it's of order 2, use trig-sub.

#### 3.2 Turning points



For a given potential function  $U(x)$ , the turning points are the points where the potential energy is equal to the total energy, i.e.  $U(x) = E$ . At turning points, the system is either just about to move, or just about to stop.

Only motion where potential is less or equal to total energy is allowed.

Bounded motion:  $[x_1, x_2]$ ; unbounded motion:  $x > x_3$

#### 3.3 Unbounded Motion:

When there is a potential well, the system could go into periodic motion with potential energy moving back and forth in the well, and position between  $x_1, x_2$ . We find period by doubling Equation 12:

$$T(E) = \sqrt{2m} \int_{x_1(E)}^{x_2(E)} \frac{dx}{\sqrt{E - U(x)}} \quad (14)$$

where we represent  $x_1(E), x_2(E)$  in terms of  $E$ .

When given  $U(x)$ , we can solve for  $x_1(E), x_2(E)$ , and then plugging in to Equation 14, we can solve for period by integration via substitution.

**Simple Pendulum** in polar coord's has the following:

$$\begin{aligned} T &= \frac{1}{2} m l^2 \dot{\theta}^2 \\ U &= mgl(1 - \cos(\theta)) \end{aligned} \quad (15)$$

It's period is given by Equation 14. Solving it gives us

$$\begin{aligned} T(E) &= 4\sqrt{\frac{l}{g}} \int_0^{\frac{\pi}{2}} \frac{du}{\sqrt{1 - k^2 \sin^2(u)}} \\ \text{where } k &= \sin\left(\frac{\theta_0}{2}\right), \sin u = \frac{1}{k} \sin\left(\frac{\theta_0}{2}\right) \end{aligned} \quad (16)$$

Equation 16 can be simplified by small angle approx into

$$T(E) = 2\pi\sqrt{\frac{l}{g}} \left( 1 + \left( \frac{\theta_0^2}{16} \right) \right) \quad (17)$$

### 3.4 Effective DOF=1 system

When the lagrangian is of the form  $L = f(\dot{x}) - g(x)$ , we can see it as a system with effective potential  $U_{\text{eff}(x)} = g(x)$ , and effective kinetic energy  $T_{\text{eff}(x)} = f(\dot{x})$ . The effective energy is therefore  $E = T_{\text{eff}} + U_{\text{eff}}$ .

## 4 Two body problem

### 4.1 Problem setup

- The two body problem considers two interacting masses with an interacting potential  $U(r_1, r_2) = U(|\vec{r}_1 - \vec{r}_2|)$ . The lagrangian is given by

$$L = \frac{1}{2} m_1 \dot{r}_1^2 + \frac{1}{2} m_2 \dot{r}_2^2 - U(|\vec{r}_1 - \vec{r}_2|) \quad (18)$$

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### 4.2 COM and relative coordinates, DOF= 6 -> DOF = 2

- Consider the following handy substitution,

$$\begin{aligned} \text{Reduced mass } \mu &= (m_1 m_2) / (m_1 + m_2) = m_1 m_2 / M; \\ \text{Center of mass } R &= (m_1 r_1 + m_2 r_2) / (M); \\ \text{relative position } \vec{r} &= \vec{r}_1 - \vec{r}_2 \end{aligned} \quad (19)$$

- Putting the two body system into relative coordinates, and represent masses with reduced mass and COM, we have the following lagrangian:

$$L = \frac{1}{2}M\dot{R}^2 + \frac{1}{2}\mu\dot{\vec{r}}^2 - U(\vec{r}) \quad (20)$$

where the first term involves only the COM motion, and the second term involves only the relative motion.

- By choosing our frame with the COM at rest and the total momentum zero, our problem is simplified to an **effective one body problem** with  $\text{DOF} = 2$ , given by

$$L = \frac{1}{2}\mu\dot{\vec{r}}^2 - U(\vec{r}) \quad (21)$$

#### 4.3 Conservation of Angular Momentum

- Angular momentum is defined as  $\vec{L} = \vec{r} \times \mu\dot{\vec{r}}$ , and is conserved here.
- Knowing  $\vec{r} \cdot \vec{L} = 0$ , the motion is in the plane perpendicular to  $\vec{L}$ . We can use polar coordinates to describe the motion,

$$L = \frac{1}{2}\mu(\dot{r}^2 + r^2\dot{\theta}^2) - U(r) \quad (22)$$

Using EL equation on Equation 22, we get

$$\begin{aligned} \frac{d}{dt} \frac{\partial L}{\partial \dot{\varphi}} &= \frac{\partial L}{\partial \varphi} \\ \Rightarrow \vec{L}_z &\equiv \mu r^2 \dot{\theta} = \text{constant} \end{aligned} \quad (23)$$

(conservation of angular momentum on z-axis)

#### 4.4 2 body problem in gravitational field

$$\begin{aligned} L &= \frac{1}{2}m_1\dot{r}_1^2 + \frac{1}{2}m_2\dot{r}_2^2 - [m_1gz_1 + m_2gz_2 + U(r)] \\ &= \left[ \frac{1}{2}M\dot{R}^2 - MgZ + \right] + \left[ \frac{1}{2}\mu\dot{\vec{r}}^2 - U(r) \right] \end{aligned} \quad (24)$$

where  $Z$  is the vertical coordinate of the CM position,  $Z = \frac{m_1z_1 + m_2z_2}{M}$

#### 4.5 Kepler's second Law

We calculate the differential of area swept by particle in polar coordinates,

$$\begin{aligned} dA &= \frac{1}{2}r^2 d\varphi \\ \Rightarrow \frac{dA}{dt} &= \frac{1}{2\mu} \vec{L}_z \\ \vec{L}_z &= 2\mu \dot{A}(\text{constant}) \end{aligned} \quad (25)$$

This is the Kepler's second law, which states that the area swept by the radius in a given time is constant.

#### 4.6 EOM for two body system

- The total energy:

$$\begin{aligned} E = T + U &= \frac{1}{2}\mu\dot{r}^2 + \frac{1}{2}\mu r^2\dot{\varphi}^2 + U(r) \\ &= \frac{1}{2}\mu\dot{r}^2 + U(r) + \frac{L_z^2}{2\mu r^2} \quad (\text{Notice } L_z = \mu r^2\dot{\varphi}) \end{aligned} \quad (26)$$

solving this ODE by integration gives

$$t(r) = \int \frac{dr}{\sqrt{\frac{2}{\mu} \left[ E - U(r) - \frac{L_z^2}{2\mu r^2} \right]}} + C \quad (27)$$

- Also from  $L_z = \mu r^2\dot{\varphi}$ , by integrating with respect to time, we get

$$\varphi(t) = \frac{L_z}{\mu} \int \frac{dt}{r^2(t)} + C' \quad (28)$$

Equation 28 and Equation 26 describe the relative motion of the two body system in terms of constants  $\{E, L_z, C, C'\}$

#### 4.7 Shape of orbit

- Equation 26 skipped a step,

$$\frac{dr}{dt} = \sqrt{\left(\frac{2}{\mu}\right) \left[ E - U(r) - \frac{L_z^2}{2\mu r^2} \right]} \quad (29)$$

this equation, combined with our beloved

$$L_z = \mu r^2\dot{\varphi} \Rightarrow d\varphi = \frac{L_z}{\mu r^2} dt \quad (30)$$

we get the equation of orbit:

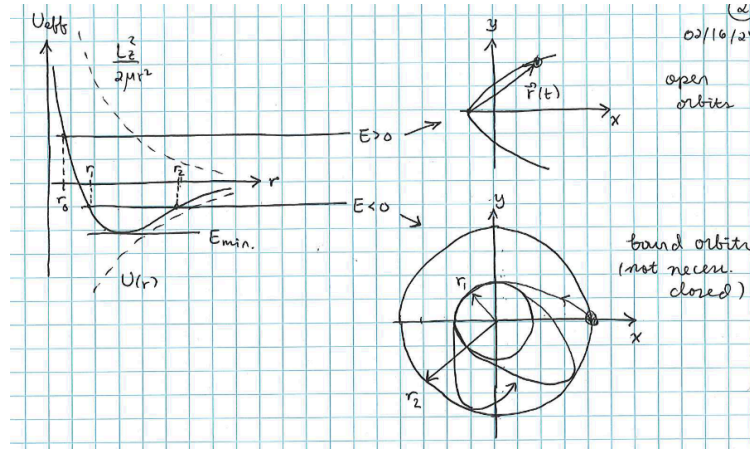
$$\begin{aligned} d\varphi &= \frac{L_z}{\sqrt{2\mu}} \frac{dr}{r^2 \sqrt{E - U(r) - \frac{L_z^2}{2\mu r^2}}} \\ \Rightarrow \varphi &= \frac{L_z}{\sqrt{2\mu}} \int \frac{dr}{r^2 \sqrt{E - U(r) - \frac{L_z^2}{2\mu r^2}}} + C \end{aligned} \quad (31)$$

#### 4.8 Effective potential and shape of orbit (Only for Attractive Potential)

$$U_{\text{eff}} = U(r) + \frac{L_z^2}{2\mu r^2}; E = \frac{1}{2}\mu\dot{r}^2 + U_{\text{eff}}(r) \quad (32)$$

- When  $r \rightarrow \infty$ ,  $U_{\text{eff}} \rightarrow U(r)$ , and when  $r \rightarrow 0$ ,  $U_{\text{eff}} \rightarrow$  centrifugal potential  $\frac{L_z^2}{2\mu r^2}$ .

- by graphing the effective potential, and given constraint of total energy  $E$ , we can analyze the shape of the orbit:



- when  $E > 0$ , the orbit is unbounded, open orbit, hyperbola.
- when  $E < 0$ , the orbit is bounded into a potential well, although not necessarily closed.
- when  $E = E_{\min}$ , the orbit is circular,  $F = -\mu \frac{v^2}{r}$

## 5 The Kepler Problem: a special case of the two body problem

### 5.1 conditions

$$U(r) = -\frac{\alpha}{r}; U_{\text{eff}} = -\frac{\alpha}{r} + \frac{L_z^2}{2\mu r^2} \quad (33)$$

### 5.2 Conic section orbits

We can prove that the orbit is a conic section given by

$$r(\varphi) = \frac{p}{1 + e \cos(\varphi)} \quad (35)$$

$$\text{where } \begin{cases} p = \frac{L_z^2}{\mu \alpha} \\ e = \sqrt{1 + \frac{2EL_z^2}{\mu \alpha^2}} \end{cases} \quad (34)$$

### 5.3 Classifications of orbits based on energy of system E

- When  $E > 0, e > 1$ , the orbit is unbounded, open orbit, hyperbola.

$$\begin{aligned} \frac{(x-c)^2}{a^2} - \frac{y^2}{b^2} &= 1 \\ \begin{cases} a = \frac{p}{e^2-1}, b = \frac{p}{\sqrt{e^2-1}}, c = ae \\ r_{\min} = \frac{p}{1+e} \end{cases} \end{aligned} \quad (36)$$

- when  $E = 0, e = 1$ , the orbit is parabola.

$$\begin{aligned} y^2 &= p^2 - 2xp, \\ r_{\min} &= \frac{p}{2} \end{aligned} \quad (37)$$

- when  $E < 0, e < 1$ , the orbit is closed, ellipse.

$$\begin{aligned} \frac{(x+c)^2}{a^2} + \frac{y^2}{b^2} &= 1, \\ \begin{cases} a = \frac{p}{1-e^2}, b = \frac{p}{\sqrt{1-e^2}}, c = ae \\ r_{\min} = \frac{p}{1+e}; r_{\max} = \frac{p}{1-e} \end{cases} \end{aligned} \quad (38)$$

- When  $E = E_{\min}, f = \frac{\mu\alpha^2}{2L_z^2}, e = 0$ , orbit is circular.  $r(\varphi) = p = \text{constant}$

## 6 More Kepler: Period, Kepler's third law

### 6.1 Orbit of each body

recall Equation 19, we can express the orbit of each body as such after some algebra:

$$\vec{r}_1 = \frac{m_2}{m_1 + m_2} \vec{r}; \vec{r}_2 = -\frac{m_1}{m_1 + m_2} \vec{r} \quad (39)$$

- when  $m_1 = m_2 \Rightarrow \vec{r}_1 = \frac{\vec{r}}{2}, \vec{r}_2 = -\frac{\vec{r}}{2}$ , COM inside  $r_1 \cap r_2$
- when  $m_1 \gg m_2 \Rightarrow \vec{r}_1 = \vec{r}, \vec{r}_2 = 0$ ,  $m_1$  is at rest,  $m_2$  orbits  $m_1$

### 6.2 Period of orbit

- $L_z = 2\mu\dot{A}$ , areal vel. is constant
- Integrating  $\dot{A}$  over a period,

$$A = \int_0^T \dot{A} dt = \frac{L_z T}{2\mu} \quad (40)$$

Since area swept over a period is the area of the ellipse, we have

$$\begin{aligned} \pi ab &= \frac{L_z T}{2\mu}, \text{ letting: } b = \sqrt{pa}, p = \frac{L_z^2}{\mu\alpha} \\ \Rightarrow T &= (2\pi a^{3/2}) \sqrt{\frac{\mu}{\alpha}} \end{aligned} \quad (41)$$

### 6.3 Conservation of Laplace-Runge-Lenz vector

$\vec{A} = \vec{v} \times \vec{L} - (\alpha\vec{r})/(r)$  is conserved, and is perpendicular to the orbit plane. We can use it to verify : conic sections, eccentricity, and period.

- conserved quantity:  $\vec{A} \cdot \vec{L} = 0, \frac{A}{\alpha} = \sqrt{1 + \frac{2EL_z^2}{\mu\alpha^2}}$

## 7 Orbital Transfer

### 7.1 Instantaneous Change in velocity

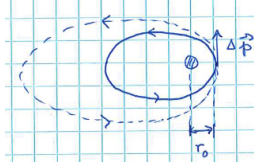


$$\begin{aligned}
(E, L_z) &\rightarrow (E', L'_z) \\
\Rightarrow (e, p) &\rightarrow (e', p')
\end{aligned} \tag{42}$$

if thrust occur when satellite is at angle  $\varphi_0$ , orbit orientation can change:

$$r(\varphi_0) = \frac{p}{1 + e \cos \varphi_0} = \frac{p'}{1 + e' \cos(\varphi_0 - \delta)} \tag{43}$$

## 7.2 Tangential thrust at perigee



at  $\varphi = 0$ , let  $v = v_{\text{init}}$ ,  $v' = v_{\text{right after}}$ ,  $\lambda = v'/v$

$$\begin{aligned}
L_z = \mu r_0 v &\Rightarrow L'_z = \mu r_0 v' = \lambda L_z \\
p' &= \lambda^2 p
\end{aligned} \tag{44}$$

From Equation 43,

$$\frac{p}{1 + e} = \lambda^2 \frac{p}{1 - e'} \Rightarrow e' = \lambda^2(1 + e) - 1 \tag{45}$$

if  $\lambda > 1$ ,  $e' > e$ , the satellite is in a higher, more elliptical orbit.

Unbound if  $\lambda$  big enough

if  $\lambda < 1$ ,  $e' < e$ , the satellite is in a lower orbit.

## 7.3 changing between circular orbits

- changing from  $R$  to  $R'$ , two thrusts( $\lambda_1, \lambda_2$ ) are needed. There is also an intermediate orbit

$$\begin{aligned}
r(\varphi) &= p'/(1 + e' \cos \varphi), \\
\text{where } p' &= \lambda_1^2 p, e' = \lambda_1^2 - 1
\end{aligned} \tag{46}$$

changed from intermediate to final,

$$\begin{aligned}
r(\varphi = \pi) &= R' = \lambda_2^2 R/(2 - \lambda_1^2) \\
\Rightarrow \lambda_1 &= \sqrt{\frac{2R'}{R + R'}}
\end{aligned} \tag{47}$$

final orbit:

$$\begin{aligned}
r(\varphi) &= R'; e'' = 0, p'' = R' \\
\Rightarrow p'' &= \lambda_2^2 p' = p'/(1 - e') \\
\Rightarrow \lambda_2 &= \sqrt{\frac{R + R'}{2R'}}
\end{aligned} \tag{48}$$

## 7.4 Verify:

using Newton 2nd,

$$\begin{aligned}
\frac{\alpha}{R^2} &= \mu \frac{v_R^2}{R} \\
\Rightarrow v_R &= \sqrt{\frac{\alpha}{\mu} R} \\
\Rightarrow \frac{V_{R'}}{V_R} &= \sqrt{\frac{R}{R'}}
\end{aligned} \tag{49}$$

verify using conservation of angular momentum,

$$\begin{aligned}
Rv(\varphi = 0) &= R'v(\varphi = \pi), \\
V_{R'} &= \lambda v(\varphi = \pi) = \lambda_2 \frac{v(\varphi = \pi)}{v(\varphi = 0)} \lambda_1 v_R \\
\Rightarrow \frac{v_{R'}}{v_R} &= \sqrt{\frac{R}{R'}}
\end{aligned} \tag{50}$$

agrees with Equation 49 !!

## 8 Small Oscillations

- Motion near a point of stable equilibrium.

### 8.1 DOF= 1 (one dimension)

- For a system of DOF = 1, with potential  $U(q)$ :
  - **stable equilibrium** at  $U(q)_{\min}$ , upward parabola, where  $F = -\frac{dU}{dq} = 0$ 
    - restoring force for small displacements  $q - q_0$  is  $F = -\frac{dU(q-q_0)}{dq}$
  - **Unstable equilibrium** at  $U(q)_{\max}$ , downward parabola, where  $F = -\frac{dU}{dq} = 0$  as well.
- Consider small deviation from point of stable equilibrium, we use Taylor expansion to show that it is really a small displacement. that is,

$$U(q) \approx U(q_0) + \frac{dU(q_0)}{dq}(q - q_0) + \left(\frac{1}{2}\right) \frac{d^2U(q_0)}{dq^2}(q - q_0)^2 + \dots \quad (51)$$

while  $\frac{dU(q_0)}{dq}(q - q_0) = 0$

letting  $x = q - q_0$ , we have

$$\begin{cases} U(x) = U(q_0) + \left(\frac{1}{2}\right) \frac{d^2U(q_0)}{dq^2} x^2 \\ \text{putting into the form of } U(x) = U(x_0) + \left(\frac{1}{2}\right) kx^2. \end{cases} \quad (52)$$

$$\Rightarrow \boxed{k = \frac{d^2U(q_0)}{dq^2} > 0}$$

we get KE, while choosing  $U(q_0) = 0$ :

$$T = \frac{1}{2} a(q)^2 \dot{q}^2 = \frac{1}{2} a(q_0 + x) \dot{x}^2 \approx \frac{1}{2} m \dot{x}^2, \text{ letting } m = a(q_0) \quad (53)$$

$$\Rightarrow \boxed{L = T - U = \frac{1}{2} m \dot{x}^2 - \frac{1}{2} kx^2}$$

#### 8.1.1 EOM for DOF = 1 small Oscillations

using EL on Equation 53, we can get the EOM for one dimensional small Oscillations:

$$m\ddot{x} = -kx$$

$$\Rightarrow \ddot{x} + \omega_0^2 x = 0, \text{ where } \boxed{\omega_0 = \sqrt{\frac{k}{m}} \text{ freq of osc.}} \quad (54)$$

by magic of ODE, EOM reduces down to:

$$\boxed{x(t) = C_1 \cos(\omega_0 t) + C_2 \sin(\omega_0 t)} \quad (55)$$

where  $C_1, C_2$  are constants

by trig magic, this could also be written as

$$x(t) = a \cos(\omega_0 t + \alpha),$$

$$\text{where } \begin{cases} a = \sqrt{C_1^2 + C_2^2} & \text{amplitude of oscillation} \\ \omega_0 & \text{frequency of oscillation} \\ \tan \alpha = C_2/C_1 & \text{phase at } t=0 \end{cases} \quad (56)$$

### 8.1.2 energy for 1D small Oscillation

checking  $\frac{\partial L}{\partial t} = 0 \Rightarrow$  energy-conservation:

$$\begin{aligned} E = T + U &= \frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2 \\ &= \frac{1}{2}ma^2\omega_0^2, [\text{constant}] \end{aligned} \quad (57)$$

### 8.1.3 Damped 1D oscillation, and Complex representation

[I dont like the how the subscripts are used in this lecture but I guess this is what we are stuck with.]

- when there is damping (friction, resistance, etc)  $F_{\text{fric}} = -\beta\dot{x}$ , the EOM becomes:

$$\begin{aligned} \ddot{x} + 2\gamma\dot{x} + \omega_0^2 x &= 0, \\ \text{where } 2\gamma &= \frac{\beta}{m}, \omega_0 = \sqrt{\frac{k}{m}} \end{aligned} \quad (58)$$

with ansatz  $x(t) = e^{rt}$ ,  $\dot{x} = re^{rt}$ ,  $\ddot{x} = r^2 e^{rt}$ , the solution to Equation 58 is:

$$\begin{aligned} r^2 + 2\gamma r + \omega_0^2 &= 0, \\ \text{which has solution } r_{\pm} &= -\gamma \pm \sqrt{\gamma^2 - \omega_0^2} \\ \Rightarrow x(t) &= C_1 e^{r_+ t} + C_2 e^{r_- t}, \end{aligned} \quad (59)$$

notice the r subscripts here:  $r_+, r_-$

### 8.1.4 underdamped, overdamped, and critically damped

Recall from your ODE class...

Equation 59 has the following 3 cases, each with different physical interpretation:

1. underdamped:

$$\gamma < \omega_0 \Rightarrow 2 \text{ complex roots: } \begin{cases} r_{\pm} = -\gamma \pm i\sqrt{\omega_0^2 - \gamma^2} = -\gamma \pm i\omega \\ \omega = \sqrt{\omega_0^2 - \gamma^2} \end{cases} \quad (60)$$

The EOM is thus a linear combination of two complex exponentials:

$$\begin{aligned}
x(t) &= e^{-\gamma t} (C_1 e^{i\omega t} + C_2 e^{-i\omega t}) \\
&= e^{-\gamma t} (A \cos(\omega t) + B \sin(\omega t)) \\
-- \text{ where } \begin{cases} A = C_1 + C_2 \\ B = i(C_1 - C_2) \end{cases} & \quad (61) \\
&= a e^{-\gamma t} \cos(\omega t + \alpha) \\
a, \alpha &\text{ are constants}
\end{aligned}$$

“The solution is a damped oscillation with frequency  $\omega$ , and amplitude exponentially decaying with time.”

## 2. Overdamped

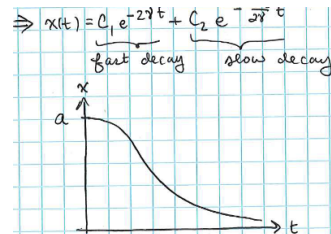
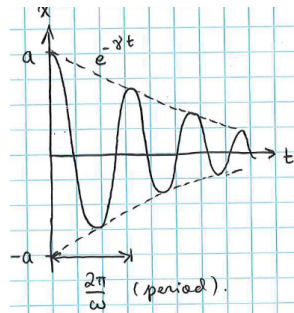
$$\gamma > \omega \Rightarrow x(t) = c_1 e^{-\gamma + \sqrt{\gamma^2 - \omega^2} t} + c_2 e^{-\gamma - \sqrt{\gamma^2 - \omega^2} t} \quad (62)$$

When

$$\begin{aligned}
\gamma \gg \omega_0, \Rightarrow \begin{cases} \gamma + \sqrt{\gamma^2 - \omega_0^2} \approx 2\gamma \\ \gamma - \sqrt{\gamma^2 - \omega^2} = \frac{\omega^2}{2\gamma} \end{cases} & \quad (63) \\
x(t) = c_1 e^{-2\gamma t} + c_2 e^{(-\omega_0^2/2\gamma)t}
\end{aligned}$$

## 3. Critically damped

$$\gamma = \omega_0 \Rightarrow x(t) = c_1 e^{-\gamma t} + c_2 t e^{-\gamma t} \quad (64)$$

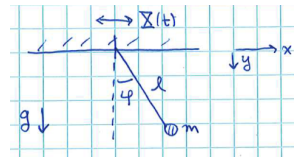


## 8.2 Forced Oscillations

When external force ( $F$ ) is applied to the system, the lagrangian becomes

$$\begin{aligned}
L &= \frac{1}{2} m \dot{x}^2 - \frac{1}{2} k x^2 + F(t)x \\
\text{EL} \Rightarrow \ddot{x} + \omega_0^2 x &= \frac{F(t)}{m}, \text{ where } \omega_0 = \sqrt{\frac{k}{m}} & (65)
\end{aligned}$$

- Example: Simple pendulum with moving pivot



$$\begin{cases} x = X + l \sin \varphi \\ y = l \cos \varphi \end{cases} \Rightarrow \begin{cases} \dot{x} = \dot{X} + l \dot{\varphi} \cos \varphi \\ \dot{y} = -l \dot{\varphi} \sin \varphi \end{cases}$$

$$\Rightarrow L = T - U$$

$$L = \frac{1}{2} m l^2 \dot{\varphi}^2 - m g l (1 - \cos \varphi) - m l \ddot{X} \sin \varphi$$

$$\text{Expand ab. } \varphi = 0 \Rightarrow L = \frac{1}{2} m l^2 \dot{\varphi}^2 - \frac{1}{2} m g l \varphi^2 - m l \ddot{X} \varphi \quad (67)$$

$$\text{EL} \Rightarrow \boxed{\ddot{\varphi} + \omega_0^2 \varphi = -\frac{\ddot{X}}{l}, \text{ where } \omega_0 = \sqrt{\frac{g}{l}}}$$

### 8.2.1 reintroducing damping via external forcing

$$\ddot{x} + 2\gamma \dot{x} + \omega_0^2 x = f(t), f(t) = \frac{F(t)}{m} \quad (68)$$

When damping  $f(t) = f_0 \cos(\Omega t)$ , solution via complex number:

$$\ddot{z} + 2\gamma \dot{z} + \omega_0^2 z = f_0 e^{i\Omega t}$$

$$\text{ansatz } z(t) = z_0 e^{i\Omega t} \Rightarrow z_0 = \frac{f_0}{\omega_0^2 + 2i\gamma\Omega + \Omega^2}$$

$$\boxed{z_0 = a(\Omega) \cos(\Omega t + \delta(\Omega)) f_0} \text{ is a particular solution, where } \quad (69)$$

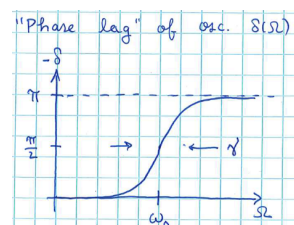
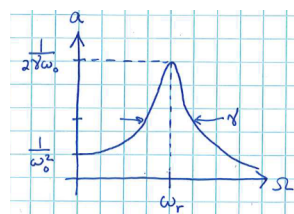
$$\begin{cases} a(\Omega) = \frac{1}{\sqrt{(\omega_0^2 - \Omega^2)^2 + (2\gamma\Omega)^2}} \\ \delta(\Omega) = \arctan\left(2\gamma \frac{\Omega}{\omega_0^2 - \Omega^2}\right) \end{cases}$$

We can study the properties of the system by looking at the amplitude and phase of the solution.

- Amplitude:

$$a(\Omega) = \frac{1}{\sqrt{(\omega_0^2 - \Omega^2)^2 + (2\gamma\Omega)^2}} \quad (70)$$

, when  $\gamma \ll \omega_0$ , response strongest and amplitude largest when  $\omega_r = \omega_0$ .



- Phase lag:  $\tan \delta(\Omega) = 2\gamma \frac{\Omega}{\omega_0^2 - \Omega^2}$

in phase as  $\Omega \rightarrow 0$ , and out of phase as  $\Omega \rightarrow \omega_0$ .

- Genral solution to sinusoidal forcing:

$$\begin{aligned}
 x(t) &= a(\Omega) f_0 \cos(\Omega t + \delta(\Omega)) + a_0 e^{-\gamma t} \cos(\omega t + \alpha) \\
 &\xrightarrow{t > \frac{1}{\gamma}} a(\Omega) f_0 \cos(\Omega t + \delta(\Omega))
 \end{aligned}
 \tag{71}$$

Forgets initial condition after time.

- Power obsorbed by oscillation

$p = F\dot{x} = m f \dot{x}$  Avg power

$$\begin{aligned}
 P_{\text{avg}} &= \frac{1}{T} \int_0^T m f \dot{x} \, dt = -\frac{1}{2} m f_0 a(\Omega) \Omega \sin \delta(\Omega) \\
 P(\Omega) &= \gamma m f_0^2 \Omega^2 a^2(\Omega)
 \end{aligned}
 \tag{72}$$

Absorption around resonance frequency  $\Omega = \omega_0 + \varepsilon$  is maximum:

$$P = \frac{\gamma m f_0^2}{4(\varepsilon^2 + \gamma^2)} \approx \frac{m f_0^2}{4\gamma}
 \tag{73}$$

## 9 Appendix

1. Taylor expansion:

$$f(x)|_0 \approx f(a) + f'(a)(x-a) + f''(a)\frac{(x-a)^2}{2} \quad (74)$$

2. small angle approximation:

$$\sin(\theta) \approx \theta \quad \cos(\theta) \approx 1 - \theta^2 \quad (75)$$