

# Vibrations and Waves by George C. King Notes

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## 1 Simple Harmonic Motion

- The equation of motion for a simple harmonic oscillator is

$$\frac{d^2x}{dt^2} = -\omega^2 x$$

where

$$\omega^2 = \frac{k}{m}$$

- The general solution of the equation of motion for a simple harmonic oscillator is

$$x = A \cos(\omega t + \phi)$$

or equivalently

$$x = a \cos \omega t + b \sin \omega t$$

- The angular frequency  $\omega$  is determined entirely by properties of the oscillator, e.g. its mass and spring coefficient

- The total energy of a harmonic oscillator is

$$E = \frac{1}{2}kA^2$$

- Nearly all potential wells have a shape that is parabolic when sufficiently close to the equilibrium position, so most oscillating systems will oscillate with SHM when the amplitude of oscillation is small
- The vibrations of nuclei in a molecule can be modeled by SHM, but only a discrete set of vibrational energies is possible, namely

$$\frac{1}{2}\hbar\omega, \frac{3}{2}\hbar\omega, \frac{5}{2}\hbar\omega, \dots$$

where  $\hbar$  is Planck's constant divided by  $2\pi$

- The total energy of a system undergoing SHM is always given by an expression of the form

$$E = \frac{1}{2}\alpha v^2 + \frac{1}{2}\beta x^2$$

where  $\alpha$  and  $\beta$  are physical constants — if we obtain this equation during the analysis of a system we know we have SHM

- The equation of motion for a system described by the energy equation above is

$$\frac{d^2x}{dt^2} = -\frac{\beta}{\alpha}x$$

## 2 The Damped Harmonic Oscillator

- The equation of motion of a damped harmonic oscillator is

$$F = ma = -kx - bv$$

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$$

$$\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + \omega_0^2x = 0$$

where  $\gamma = b/m$  and  $\omega_0^2 = k/m$

- $\omega_0$  is known as the **natural frequency of oscillation**, i.e. the oscillation frequency if there were no damping
- **Light damping / underdamped**
  - The motion is still oscillatory but the amplitude decreases exponentially

- This occurs when  $\gamma^2/4 < \omega_0^2$
- The general solution is

$$x = A_0 e^{-\gamma t/2} \cos(\omega t + \phi)$$

where  $A_0$  is the initial amplitude

- Successive maxima decrease by the same fractional amount

$$\frac{A_n}{A_{n+1}} = e^{\gamma T/2}$$

- The natural logarithm of  $A_n/A_{n+1}$  is called the **logarithmic decrement**

$$\ln \left( \frac{A_n}{A_{n+1}} \right) = \frac{\gamma T}{2}$$

- **Heavy damping / overdamped**

- The motion is not oscillatory and returns sluggishly to the equilibrium position
- This occurs when  $\gamma^2/4 > \omega_0^2$
- The general solution is

$$\begin{aligned} x &= e^{-\gamma t/2} [Ae^{\alpha t} + Be^{-\alpha t}] \\ &= Ae^{(\alpha - \gamma/2)t} + Be^{-(\alpha + \gamma/2)t} \end{aligned}$$

where  $\alpha = \sqrt{\gamma^2/4 - \omega_0^2}$

- **Critical damping**

- The motion is not oscillatory and returns as quickly as possible to the equilibrium position
- This occurs when  $\gamma^2/4 = \omega_0^2$
- The general solution is

$$x = Ae^{-\gamma t/2} + Bte^{-\gamma t/2}$$

- The total energy of an underdamped system decreases over time

$$E = E_0 e^{-\gamma t}$$

where  $E_0$  is the initial energy of the system

- The **decay time** or **time constant** of the system  $\tau = 1/\gamma$  is the time it takes for its energy to decrease by a factor of  $e$

- The **quality factor** of a harmonic oscillator is a dimensionless value that gives a measure of the degree of damping

$$Q = \frac{\omega_0}{\gamma}$$

where large values indicate little damping and small values indicate more damping

- The quality factor can also be used as a measure of fraction of energy lost (i.e.  $\Delta E/E$ ) per cycle  $2\pi/Q$  or per radian  $1/Q$

### 3 Forced Oscillations

- The equation of motion for an undamped forced harmonic oscillator is

$$m \frac{d^2 x}{dt^2} + kx = F_0 \cos \omega t$$

the general solution of which is

$$x = A(\omega) \cos(\omega t - \delta)$$

where

$$A(\omega) = \frac{F_0}{k(1 - \omega^2/\omega_0^2)} \text{ and } \delta = 0$$

for  $\omega < \omega_0$  and

$$A(\omega) = -\frac{F_0}{k(1 - \omega^2/\omega_0^2)} \text{ and } \delta = \pi$$

for  $\omega > \omega_0$

- From the above it can be seen that:
  - $A(\omega) \rightarrow F_0/k$  as  $\omega \rightarrow 0$
  - $A(\omega) \rightarrow \infty$  as  $\omega \rightarrow \omega_0$
  - $A(\omega) \rightarrow 0$  as  $\omega \rightarrow \infty$
- The equation of motion for a damped forced harmonic oscillator is

$$\frac{d^2 x}{dt^2} + \gamma \frac{dx}{dt} + \omega_0^2 x = \frac{F_0}{m} \cos \omega t$$

where  $\gamma = b/m$  and  $\omega_0^2 = k/m$  the general solution of which is

$$x = A(\omega) \cos(\omega t - \delta)$$

where

$$A(\omega) = \frac{F_0}{m[(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2]^{1/2}}$$

and

$$\delta = \arctan \frac{\omega \gamma}{\omega_0^2 - \omega^2}$$

- From the above it can be seen that:

- $A(\omega) \rightarrow F_0/k$  as  $\omega \rightarrow 0$
- $A(\omega) \rightarrow F_0\omega_0/k\gamma$  as  $\omega \rightarrow \omega_0$
- $A(\omega) \rightarrow 0$  as  $\omega \rightarrow \infty$

- $A(\omega)$  is maximised when its denominator is minimised, leading to

$$\omega_{\max} = \omega_0(1 - \gamma^2/2\omega_0^2)^{1/2}$$

and thus

$$A_{\max} = \frac{F_0\omega_0/\gamma}{k(1 - \gamma^2/4\omega_0^2)^{1/2}}$$

- The power absorbed by a damped oscillator to sustain its motion is exactly equal to the rate at which the energy is dissipated, i.e.

$$\begin{aligned} P(t) &= bv(t) \times v(t) \\ &= b[v(t)]^2 \\ &= v[v_0(t)]^2 \sin^2(\omega t - \delta) \end{aligned}$$

- The average power absorbed over one cycle is

$$\bar{P}(\omega) = \frac{b[v_0(\omega)]^2}{2} = \frac{\omega^2 F_0^2 \gamma}{2m[(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2]}$$

- From the above it can be seen that:

- $\bar{P}(\omega) \rightarrow 0$  as  $\omega \rightarrow 0$
- $\bar{P}(\omega) \rightarrow F_0^2/2m\gamma$  as  $\omega \rightarrow \omega_0$
- $\bar{P}(\omega) \rightarrow 0$  as  $\omega \rightarrow \infty$

- The **power resonance curve** of an oscillating system graphs the average power absorbed by the system over a cycle to the driving frequency
- The **full width at half height** of a power resonance curve is the width of the curve at height  $P_{\max}/2$ , is a measure of the sharpness of the system's response to an applied force, and is equal to  $\omega_{\text{fwhh}} = \gamma = \omega_0/Q$
- From the above it can be seen that

$$Q = \frac{\omega_0}{\gamma} = \frac{\omega_0}{\omega_{\text{fwhh}}}$$

- A resonance circuit can be used to amplify AC signals around a particular frequency by the  $Q$ -factor of the circuit — this makes them useful in radio receivers to tune a specific frequency

- When a driving force is first applied to a system, the system will be inclined to oscillate at its natural frequency  $\omega_0$ . The behaviour of the system is described by the sum of two oscillations, one at frequency  $\omega_0$  and the other at  $\omega$ . Eventually the  $\omega_0$  oscillations die out leaving the system in its **steady state** condition. The initial behaviour is referred to as its **transient response**.
- The equation of motion for damped forced oscillations is the second-order nonhomogeneous linear differential equation

$$\frac{d^2x}{dt^2} + \gamma \frac{dx}{dt} + \omega_0^2 x = \frac{F_0}{m} \cos \omega t.$$

The oscillations at frequency  $\omega_0$  present only during the transient response are described by the complementary function of this equation, i.e. a fundamental set of solutions of the associated homogeneous differential equation, and the oscillations at frequency  $\omega$  are described by a particular solution of this equation.

- If  $z = x + yi$ , the **complex conjugate** of  $z$  is  $z^* = x - yi$
- The product of a complex number with its conjugate is  $zz^* = x^2 + y^2$
- The **modulus** of a complex number is defined as  $|z| = \sqrt{zz^*} = \sqrt{x^2 + y^2}$
- Division of complex numbers can be performed like so

$$\frac{z_1}{z_2} = \frac{z_1 z_2^*}{z_2 z_2^*} = \frac{(x_1 + iy_1)(x_2 - iy_2)}{x_2^2 + y_2^2} = \frac{(x_1 x_2 + y_1 y_2) + i(x_2 y_1 - x_1 y_2)}{x_2^2 + y_2^2}$$

- An **Argand diagram** is two-dimensional graph where the  $x$ -axis is used as the real axis and the  $y$ -axis is used as the imaginary axis
- Using **Euler's formula**

$$e^{ix} = \cos x + i \sin x$$

a complex number can be represented as

$$z = x + iy = r(\cos \theta + i \sin \theta) = ze^{i\theta}$$

where  $r$  is the modulus  $|z|$  and  $\theta$  is the angle of  $z$  from the positive  $x$ -axis known as its **argument**

- Multiplication of complex numbers is equivalent to rotation and scaling in the complex plane

$$r_1 e^{i\theta} \times r_2 e^{i\phi} = r_1 r_2 e^{i(\theta+\phi)}$$

- Phasor diagrams can be represented on the complex plane with phasors as complex numbers  $z = Ae^{i(\omega t + \phi)}$  and their projection onto the  $x$ -axis as their real components
- Differentiation with respect to time of a complex phasor is equivalent to multiplication by  $i\omega$

## 4 Coupled Oscillators

- Systems of two or more coupled oscillators can oscillate in multiple ways called **normal modes**, each with its own frequency called the **normal frequency**
- In a normal mode, each oscillator oscillates at the same frequency
- Without damping, once a system is in a normal mode it stays there
- The equations of motion of a system of coupled oscillators are a system of differential equations and thus the movements of the oscillators are described by a linear combination of the solutions of that system
- Those equations of motion are often intertwined and involve multiple variables, e.g. the positions of two pendulums  $x_1$  and  $x_2$ . It's possible to introduce new variables called **normal coordinates** that result in independent solutions in one variable, e.g.  $q_1 = x_a + x_b$  and  $q_2 = x_a - x_b$
- Energy never flows from one normal mode to another
- In general it's difficult to determine the normal modes of the system a priori. A more general approach is to take advantage of the knowledge that in a normal mode all oscillators will oscillate at the same frequency and:
  1. assume solutions of the form  $A \cos \omega t$ ,  $B \cos \omega t$ , etc.,
  2. substitute them into the equations of motion, and
  3. rearrange to remove the constants  $A$ ,  $B$ , etc. and solve for  $\omega$
- There are as many normal modes as there are degrees of freedom in the system, e.g. two coupled oscillators moving in one dimension have 2 normal modes, three coupled oscillators moving on two dimensions have 6 normal modes, etc.
- Coupled oscillators experience large amplitude oscillations when the driving frequency is close to the normal frequency
- The motion of driven coupled oscillators may be solved in a similar fashion to their free moving counterparts:
  1. Determine the equations of motion for the oscillators
  2. Combine the equations in such a way that the normal coordinates are evident
  3. Convert the equations to use normal coordinates
  4. Solve the resulting second-order nonhomogeneous linear differential equations by assuming solutions of the form  $C_1 \cos \omega_1 t$ , etc.

5. Convert the solutions back from normal coordinates

- Oscillations that occur along the line connecting oscillators are called **longitudinal oscillations**
- Oscillations that occur perpendicular to the line connecting oscillators are called **transverse oscillations**

## 5 Travelling Waves

- The equation of a wave moving at velocity  $v$  in the positive  $x$  direction is of the form

$$y(x, t) = f(x - vt)$$

- The equation of a wave moving at velocity  $v$  in the negative  $x$  direction is of the form

$$y(x, t) = g(x + vt)$$

- The general form of any transverse wave motion can be written as

$$y = f(x - vt) + g(x + vt)$$

- The **wavelength**  $\lambda$  of a wave is the length of one complete pattern of the wave, e.g. between two maxima
- When the displacements of a wave lie in a single plane, e.g. the  $x$ - $y$  plane, it is said to be **linearly polarised**
- The frequency  $f$ , wavelength  $\lambda$ , and velocity  $v$  of a wave are related by the expression

$$f\lambda = v$$

- The frequency  $f$  and period  $T$  of a wave are related by the expression

$$f = \frac{1}{T}$$

- The **wavenumber** of a wave

$$k = \frac{2\pi}{\lambda}$$

is a measure of radians per unit distance

- The **wave equation** in one dimension is

$$\frac{\partial^2 \psi}{\partial t^2} = v^2 \frac{\partial^2 \psi}{\partial x^2}$$

and its general solution is

$$\psi = f(x - vt) + g(x + vt)$$



- An intuition for the wave equation is “the acceleration experienced by a point on the wave at a particular time is a constant multiple of the curvature of the wave at that point”
- The velocity of a wave in a taut string  $v$  is

$$v = \sqrt{\frac{T}{\mu}}$$

where  $T$  is the tension in the string and  $\mu$  is its mass per unit length

- The total kinetic and potential energies contained within one wavelength of a sinusoidal wave

$$y = A \sin(kx - \omega t)$$

are equal and have the value

$$\frac{1}{4} \mu \omega^2 A^2 \lambda$$

meaning the total energy is

$$\frac{1}{2} \mu \omega^2 A^2 \lambda$$

- The power of a sinusoidal wave, i.e. the energy carried by the wave past a point per unit time, is

$$P = \frac{1}{2} \mu \omega^2 A^2 v$$

- When a wave encounters a discontinuity, some fraction of the wave is transmitted and the remaining fraction is reflected
- The **incident wave** is the original wave
- On either side of a discontinuity, the displacement and the gradient must be the same at all times
- The ratio of the transmitted amplitude to the incident amplitude is

$$\frac{A_2}{A_1} = \frac{2k_1}{k_1 + k_2} = \frac{2\sqrt{\mu_1}}{\sqrt{\mu_1} + \sqrt{\mu_2}} = T_{12}$$

where  $k_n$  is the wave number of each medium,  $\mu_n$  is the mass per unit length of each medium, and  $T_{12}$  is called the **transmission coefficient of amplitude**

- The transmission coefficient of amplitude is a positive value in the range  $(0, 2)$ , i.e. the transmitted wave is always in phase with the incident wave

- The ratio of the reflected amplitude to the incident amplitude is

$$\frac{B_1}{A_1} = \frac{k_1 - k_2}{k_1 + k_2} = \frac{\sqrt{\mu_1} - \sqrt{\mu_2}}{\sqrt{\mu_1} + \sqrt{\mu_2}} = R_{12}$$

where  $R_{12}$  is called the **reflection coefficient of amplitude**

- The reflection coefficient of amplitude is a value in the range  $(-1, 1)$ , i.e. if  $\mu_1 > \mu_2$  the reflected wave will be in phase with the incident wave and if  $\mu_1 < \mu_2$  it will be  $90^\circ$  out of phase
- The wave equation in two dimensions is

$$\frac{\partial^2 \psi}{\partial t^2} = v^2 \left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} \right)$$

- For a sinusoidal wave travelling in two dimensions, the solution to the wave equation is

$$z(x, y, t) = A \cos(k_1 x + k_2 y - \omega t)$$

which is a planar wave with velocity

$$v = \sqrt{\frac{S}{\sigma}} = \frac{\omega}{\sqrt{k_1^2 + k_2^2}} = \frac{\omega}{k}$$

and angle from the positive  $x$ -axis  $\phi$  where

$$\tan \phi = -\frac{k_1}{k_2}$$

- The wave equation for two-dimensional waves of circular symmetry is

$$\frac{\partial^2 z}{\partial r^2} + \frac{1}{r} \frac{\partial z}{\partial r} = \frac{1}{v^2} \frac{\partial^2 z}{\partial t^2}$$

and its solutions involve Bessel functions but for large  $r$  it can be simplified to

$$\frac{\partial^2 z}{\partial r^2} = \frac{1}{v^2} \frac{\partial^2 z}{\partial t^2}$$

which has the same form as the one-dimensional wave equation with solutions of the form

$$z(r, t) = A \cos(kr - \omega t)$$

## 6 Standing Waves

- In a standing wave, a **node** is a point whose displacement is 0 at all times and an **antinode** is a point that experiences that maximum displacement

- In a standing wave, each individual particle undergoes SHM about its equilibrium position but different particles have different amplitudes
- The general equation for a standing wave on a string is

$$y_n(x, t) = A_n \sin\left(\frac{n\pi}{L}x\right) \cos \omega_n t$$

where

$$\omega_n = \frac{n\pi v}{L}$$

and  $n = 1, 2, 3, \dots$  corresponds to a different standing wave pattern or **mode**

- The first normal mode can also be called the **fundamental mode**
- The period of a standing wave is

$$T = \frac{2\pi}{\omega_n} = \frac{2L}{nv}$$

- The wavelength of a standing wave is

$$\lambda_n = \frac{2L}{n}$$

- The wavenumber of a standing wave is

$$k_n = \frac{n\pi}{L}$$

- Using the definition of the wavenumber of a standing wave, the general equation can be rewritten

$$y_n(x, t) = A_n \sin k_n x \cos \omega t$$

- A standing wave is a superposition of two travelling waves of equal frequency and amplitude travelling in opposite directions
- The total energy of a string vibrating in the  $n$ -th mode is

$$E_n = \frac{1}{4} \mu L A_n^2 \omega_n^2$$

- Standing waves are the normal modes of a vibrating string
- The superposition principle states that if  $y_1(x, t)$  and  $y_2(x, t)$  are both solutions to the wave equation, then so is  $c_1 y_1(x, t) + c_2 y_2(x, t)$
- In general, the motion of a vibrating string can be expressed as a superposition of normal modes of the string, i.e.

$$y(x, t) = \sum_n y_n(x, t) = \sum_n A_n \sin\left(\frac{n\pi}{L}x\right) \cos \omega_n t$$

- Any function  $f(x)$  where  $f(0) = f(L) = 0$  can be written as a superposition of sine waves

$$f(x) = \sum_n A_n \sin\left(\frac{n\pi}{L}x\right)$$

where

$$A_n = \frac{2}{L} \int_0^L dx \sin\left(\frac{n\pi}{L}x\right) f(x), \quad n = 1, 2, \dots$$

- This works because  $\sin \frac{m\pi}{L}x$  and  $\sin \frac{n\pi}{L}x$  are orthogonal when  $m \neq n$ , i.e.

$$\int_0^L dx \sin\left(\frac{m\pi}{L}x\right) \sin\left(\frac{n\pi}{L}x\right) = 0, \quad m \neq n$$

but

$$\int_0^L dx \sin^2\left(\frac{n\pi}{L}x\right) = \frac{L}{2}$$

so integrating the product of  $\sin\left(\frac{n\pi}{L}x\right)$  and  $f(x)$  in  $A_n$  effectively “picks out” the amplitude of the  $n$ -th normal mode

- The total energy of a vibrating string expressed as a superposition of normal modes is given by

$$E = \sum_n E_n = \sum_n \frac{1}{4} \mu L A_n^2 \omega_n^2 = \frac{1}{4} \mu L \sum_n A_n^2 \omega_n^2$$

## 7 Interference and Diffraction of Waves

- If two waves are emitted from the same source, travel different distances, and recombine, the difference in distance travelled  $s$  determines the shape of the resulting wave:

- If  $s$  is an integral multiple of  $\lambda$  the waves are said to be **in phase** and there is **constructive interference** and the amplitude of the resulting wave is double the amplitude of the original waves

$$s = n\lambda, \quad n = 0, \pm 1, \pm 2, \dots$$

or

$$\phi = 2n\pi, \quad n = 0, \pm 1, \pm 2, \dots$$

- If  $s$  is an odd integral multiple of  $\lambda/2$  the waves are said to be **out of phase** and there is **destructive interference** and the amplitude of the resulting wave is 0

$$s = \left(n + \frac{1}{2}\right) \lambda, \quad n = 0, \pm 1, \pm 2, \dots$$

or

$$\phi = (2n + 1)\pi, \quad n = 0, \pm 1, \pm 2, \dots$$

- Other values of  $s$  will result in behaviour somewhere between these two extremes
- **Huygen's principle** states that each point on a primary wavefront acts as a source of secondary wavelets such that the wavefront at some later time is the envelope of these wavelets, i.e.
  1. For each point on a primary wavefront draw an arc of radius  $v\Delta t$  in the direction of travel where  $v$  is the velocity of the wave
  2. The envelope of the resulting arcs is the shape of the wave at time  $t + \Delta t$
- Two waves are said to be **coherent** if their frequency and waveform are identical
- **Young's double-slit experiment** works via **division of wavefront** where a single source wave is sent through two narrow slits and the resulting waves interfere with each other on a far away detector
- Interference can also occur via **division of amplitude** where a single source wave is split via e.g. a semi-silvered mirror
- The bending or spreading of waves around obstacles is called **diffraction**
- If a test point  $P$  is sufficiently far from a slit causing diffraction that the secondary wavelets have become plane waves we have **Fraunhofer diffraction**
- If the source of the primary waves or a test point  $P$  is too close to a slit causing diffraction that the curvature of the incoming or outgoing wavefronts must be taken into consideration we have **Fresnel diffraction**

## 8 The Dispersion of Waves

- A medium in which the velocity of a wave depends on its frequency is called a **dispersive medium**
- A **monochromatic wave** is one that has a single frequency and wavelength
- A **modulated wave** consists of the superposition of a group of waves of different frequencies
- Modulation of two waves with similar frequencies leads to **beats** — a periodic shift between constructive and destructive interference of the two waves
- In a dispersive medium the frequency  $\omega$  is a function of the wavenumber  $k$ :  $\omega = \omega(k)$

- The **phase velocity** is the velocity of the carrier wave

$$v = \frac{\omega}{k}$$

where  $\omega$  is the mean frequency and  $k$  is the mean wave number

- The **group velocity** is the velocity of the modulated wave

$$v_g = \frac{d\omega}{dk}$$

or

$$v_g = v - \lambda \frac{dv}{d\lambda}$$

- The **dispersion relation** for a medium describes how the frequency of a wave  $\omega$  depends on the wavenumber  $k$
- The **bandwidth theorem** relates the product of the width  $\Delta x$  of a wave packet and its wavenumber spread  $\Delta k$

$$\Delta x \Delta k \approx 2\pi$$

or equivalently the product of the duration of the pulse  $\Delta t$  and its frequency spread  $\Delta \omega$

$$\Delta t \Delta \omega \approx 2\pi$$