Massachusetts Institute of Technology

Physics 8.03 Spring 2004

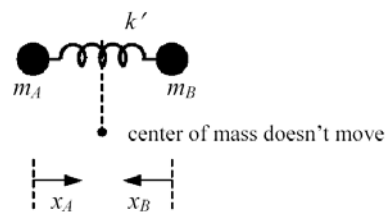
Final Exam Solutions

Thursday, December 16, 2004

Solution for Problem 1 – Coupled Oscillators

(a) If $m_A = \infty$, then $\omega_A = 0$ and $\omega_B = \sqrt{\frac{k'+k}{m_B}}$.

(b) If $k = 0$, then m_A, m_B and k' form an isolate system and the center of mass of this system doesn't move. Therefore,



$$m_A x_A = -m_B x_B \tag{1}$$

The force applied on m_A is given by

$$m_A \ddot{x}_A = -k'(x_A - x_B) \tag{2}$$

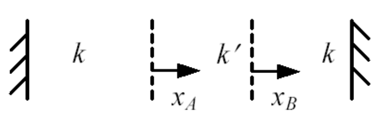
Solving them gives

$$\ddot{x}_A + x_A k' \Big(\frac{m_A + m_B}{m_A m_B}\Big) = 0 \quad \Rightarrow \quad \omega = \sqrt{\frac{k'}{M}} \tag{3}$$

where $M = \frac{m_A m_B}{m_A + m_B}$ is called the "reduced mass".

(c) If $k' = 0$, then $\omega_A = \sqrt{\frac{k}{m_A}}$ and $\omega_B = \sqrt{\frac{k}{m_B}}$.

(d) For the general situation, the coupled equations of motion are



$$m_A \ddot{x}_A = -k x_A + k'(x_B - x_A) \tag{4}$$
$$m_B \ddot{x}_B = -k x_B - k'(x_B - x_A) \tag{5}$$

(e) Assume that $x_A = A\cos\omega t$ and $x_B = B\cos\omega t$. The equations of motions become

$$-\omega^2 A + \frac{k+k'}{m_A}A - \frac{k'}{m_A}B = 0 \tag{6}$$

$$-\omega^2 B + \frac{k+k'}{m_B}B - \frac{k'}{m_B}A = 0 \tag{7}$$

rewrite them with A and B as the variables

$$A\Big(\omega^2 - \frac{k+k'}{m_A}\Big) + \frac{k'}{m_A}B = 0 \tag{8}$$

$$A\frac{k'}{m_B} + \Big(\omega^2 - \frac{k+k'}{m_B}\Big)B = 0 \tag{9}$$

for A and B have non-zero root, the determinant should be equal to zero, that is

$$\Big(\omega^2 - \frac{k+k'}{m_A}\Big)\Big(\omega^2 - \frac{k+k'}{m_A}\Big) - \frac{k'^2}{m_A m_B} = 0 \tag{10}$$

$$\omega^4 - \omega^2(k+k')\Big(\frac{1}{m_A} + \frac{1}{m_B}\Big) + \frac{(k+k')^2 - k'^2}{m_A m_B} = 0 \tag{11}$$

The solutions for ω are

$$\omega_{1,2}^2 = \frac{p}{2} \pm \frac{1}{2}\sqrt{p^2 - 4q} = \frac{p}{2} \pm \sqrt{\frac{p^2}{4} - q} \tag{12}$$

where $p = (k+k')\Big(\frac{1}{m_A} + \frac{1}{m_B}\Big)$ and $q = \frac{(k+k')^2 - k'^2}{m_A m_B}$.

Solution for Problem 2 – Dispersive String

(a) The phase velocity is

$$v_p = \frac{\omega}{k} = \sqrt{\frac{T}{\mu} + \alpha k^2} \tag{13}$$

(b) The group velocity is

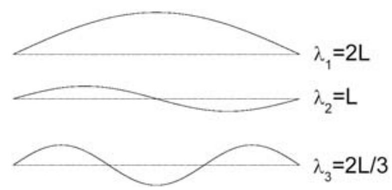
$$v_g = \frac{d\omega}{dk} = \sqrt{\frac{T}{\mu} + \alpha k^2} + \frac{\alpha k^2}{\sqrt{\frac{T}{\mu} + \alpha k^2}} = \frac{\frac{T}{\mu} + 2\alpha k^2}{\sqrt{\frac{T}{\mu} + \alpha k^2}} \tag{14}$$

(c) There are three normal oscillation modes of the string
The wave numbers $k_n = \frac{n\pi}{L}$ and the frequencies $\omega_n = v_{p_n} k_n = \frac{2\pi}{\lambda_n} v_{p_n}$. Therefore

$$\omega_1 = \frac{\pi}{L}\sqrt{\frac{T}{\mu} + \alpha(\frac{\pi}{L})^2} \tag{15}$$

$$\omega_2 = \frac{2\pi}{L}\sqrt{\frac{T}{\mu} + \alpha(\frac{2\pi}{L})^2} \tag{16}$$

$$\omega_3 = \frac{3\pi}{L}\sqrt{\frac{T}{\mu} + \alpha(\frac{3\pi}{L})^2} \tag{17}$$



$$y(x,t) = \sin\left(\frac{\pi x}{L}\right)\cos(\omega_1 t) + 4\sin\left(\frac{2\pi x}{L}\right)\cos(\omega_2 t) + 9\sin\left(\frac{3\pi x}{L}\right)\cos(\omega_3 t) \tag{18}$$

(d) The frequencies are not integer multiples. It could be a long wait for the string to return to the shape $y(x,0)$, and it may NEVER happen !

Solution for Problem 3 – Transmission Line

(a) The voltage wave is $V_i(z<0) = V_0\cos(\omega t - kz)$.

(b) For $Z_L = 0$, the circuit is shorted at $z=0$, thus $V_t = 0$ and $\frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0} = -1 \quad \Rightarrow \quad V_r = -V_i$.

(c) At $z=0$, we have 2 resistors parallel, each is 100Ω. Thus the net impedance at $z=0$ is 50Ω.

(d) Since the effective (net) impedance is the same as Z_0 (both are 50Ω), we have an impedance-matched situation, i.e., $V_r = 0$, thus $V_t = V_i$.

$$\frac{V_r}{V_i} = \frac{50-50}{100} = 0 \tag{19}$$

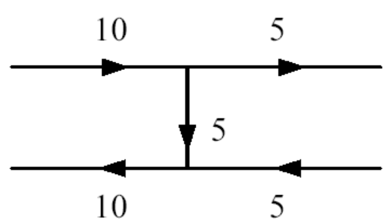
(e) The maximum incident current $|I_{i_{max}}| = \frac{|V_{i_{max}}|}{Z_0} = 10$A. $I_r = 0$ (see part (d)).

(i) thus 10A will be the maximum current in the lower wire for $z<0$.

(ii) The current splits equally between the load and the second transmission wire. Thus I_{max} through the load is 5A.

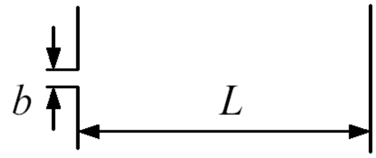
(iii) upper wire for $z>0$: $I_{max} = 5$A.

(iv) lower wire for $z>0$: $I_{max} = 5$A.



Solution for Problem 4 – Design your own pinhole camera

See the solution to problem 11.4. The best resolution is achieved when $1.2L\lambda \simeq b^2$, where b is the diameter of the circular hole.
Given $L = 0.7$m, and $\lambda = 5\times10^{-7}$m, thus $b \simeq 0.65$mm.



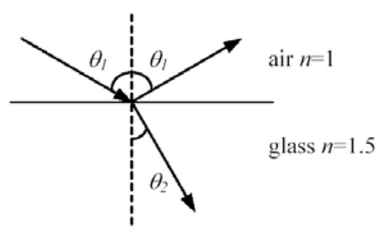
Solution for Problem 5 – Reflection of Light

(a) Snell's law $\sin\theta_1 = 1.5\sin\theta_2$, $\theta_1 = 40°$ $\Rightarrow$ $\theta_2 \simeq 25.4°$. Since the incident light is unpolarized, we may assume that the intensity of the parallel and the perpendicular components are each 50% of the incident light intensity. The reflectivity for parallel and perpendicular components are

$$r_\parallel = \frac{-\tan(\theta_1-\theta_2)}{\tan(\theta_1+\theta_2)} \simeq \frac{-0.26}{2.18} \simeq -0.12 \tag{20}$$

$$r_\perp = \frac{-\sin(\theta_1-\theta_2)}{\sin(\theta_1+\theta_2)} \simeq \frac{-0.25}{0.91} \simeq -0.28 \tag{21}$$

thus $r_\parallel^2 \simeq 0.014$, $r_\perp^2 \simeq 0.077$. The fraction of the incoming 10kW that is reflected is 0.5(0.014+0.077)=4.55%.



(b) Degree of linear polarization: $\frac{0.077-0.014}{0.077+0.014} \simeq 0.69 \simeq 70\%$ linearly polarized in favor of the $\perp$ direction.
Notice for $\theta_1 = 56°$ (the Brewster angle), $r_\parallel = 0$ and the reflected light would have been 100% linearly polarized in the $\perp$ direction.

Solution for Problem 6 – Oscillator in Viscous Medium

(a) The equation of motion of m is

$$m\ddot{x} = -kx - b\dot{x} \tag{22}$$

that is,

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = 0 \tag{23}$$

where $\frac{k}{m} = \omega_0^2$ and $\frac{b}{m} = \gamma$.

(b) Now the equation of motion of m is

$$m\ddot{x} = -kx - b\dot{x} + b\dot{d}_1 \tag{24}$$

where $d_1 = D_1\cos(\omega t)$. In terms of ω_0 and γ,

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = -\gamma\omega D_1\sin(\omega t) \tag{25}$$

(c) The steady state amplitude is

$$|A| = \frac{\gamma\omega D_1}{\sqrt{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}} \tag{26}$$

(d) For this case, the equation of motion of m is

$$m\ddot{x} = -k(x - d_2) - b\dot{x} + b\dot{d}_1 \tag{27}$$

where $d_2 = D_2 \cos(\omega t + \phi)$. In terms of ω_0 and γ,

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = -\gamma\omega D_1 \sin(\omega t) + \omega_0^2 D_2 \cos(\omega t + \phi). \tag{28}$$

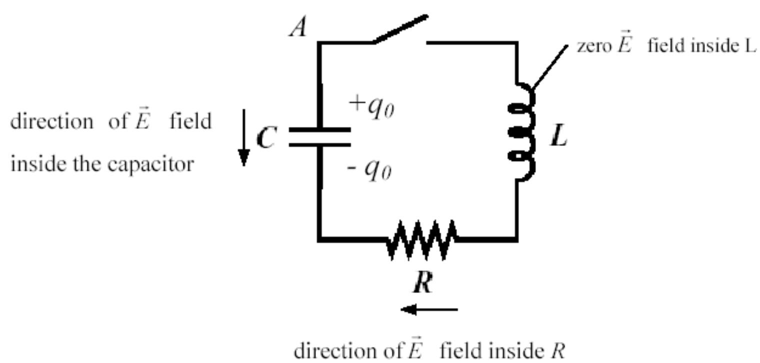
(e) In the absence of a driver, there is no motion in steady state. This will be the case when

$$\gamma\omega D_1 \sin(\omega t) = \omega_0^2 D_2 \cos(\omega t + \phi) \tag{29}$$

Thus, $D_2 = \frac{\gamma\omega D_1}{\omega_0^2}$ and $\phi = -\frac{\pi}{2}$.

Solution for Problem 7 – Discharging a Capacitor

(a)



I close the switch. A current will start flowing in clockwise direction. Faraday's law

$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial \phi_B}{\partial t} \tag{30}$$

I start at A and go clockwise and return to A.
$\oint_{A \to A} \neq 0$, Kirchhoff's voltage rule does NOT apply! Instead

$$0 + IR - V_c = -L\frac{dI}{dt} \tag{31}$$

Here $V_c = \frac{q}{C}$ and $I = -\frac{dq}{dt}$.
Notice I is clockwise, thus q decreases in time. Therefore $I = -\frac{dq}{dt}$.
It now follows from (31)

$$-L\ddot{q} - \dot{q}R - \frac{q}{C} = 0 \quad \Rightarrow \quad \ddot{q} + \frac{R}{L}\dot{q} + \frac{q}{LC} = 0 \tag{32}$$

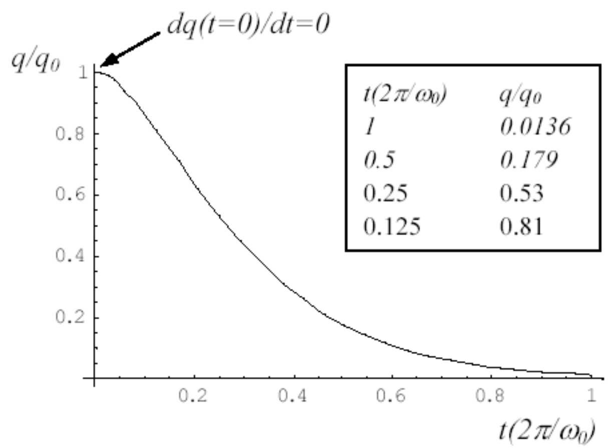
(b) $q(t=0) = q_0$, $\dot{q}(t=0) = 0$.

(c) critical damping $\omega_0 = \frac{\gamma}{2}$
$\omega_0 = \frac{1}{\sqrt{LC}}$, $\gamma = \frac{R}{L}$, thus: $\frac{1}{\sqrt{LC}} = \frac{R}{2L} \quad \Rightarrow \quad R = 2\sqrt{\frac{L}{C}}$.

(d) $q(t) = (A_1 + A_2 t)e^{-\frac{\gamma}{2}t}$ where A_1 has the dimension of charge and A_2 has the dimension of current.
$q(0) = q_0 \Rightarrow A_1 = q_0$
$\dot{q}(t) = -\frac{\gamma}{2}e^{-\frac{\gamma}{2}}(A_1 + A_2 t) + A_2 e^{-\frac{\gamma}{2}t}$
$t = 0$, $\dot{q} = 0$, $-\frac{\gamma}{2}A_1 + A_2 = 0 \Rightarrow A_2 = \frac{\gamma}{2}q_0$
Thus,

$$q(t) = q_0(1 + \frac{\gamma}{2}t)e^{-\frac{R}{2L}t} \tag{33}$$

(e) For the case of critical damping



Solution for Problem 8 – Interferometric Radio Telescope

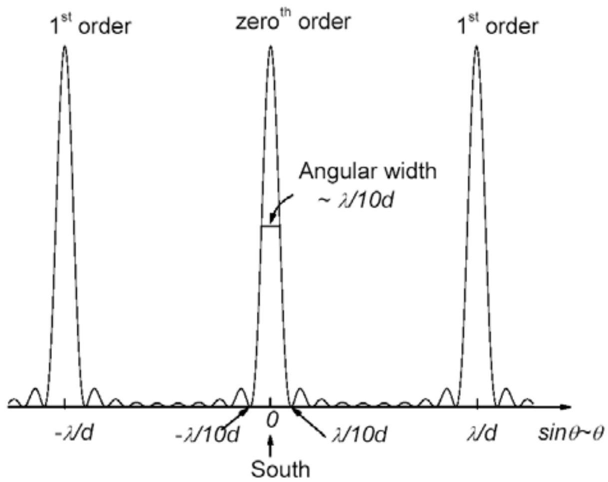
(a) The intensity pattern of this array of telescopes is sketched below
$\lambda = 6$cm, $d = 800$m $\Rightarrow \lambda/d \simeq 7.5 \times 10^{-5}$radians.

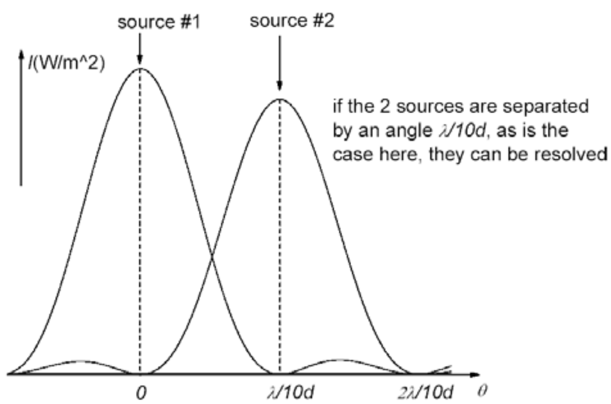
(b) The angular distance from zero to first order is $\frac{\lambda}{d} \simeq 7.5 \times 10^{-5}$radians$\simeq$ 15arcsec.

(c) The angular width of all orders is about $\frac{\lambda}{10d} \simeq 7.5\mu$rad$\simeq$ 1.5arcsec.

(d) The size of the radio dishes does not enter into the angular resolution. A larger dish, however, is more sensitive, just like a larger optical telescope (ground based). Larger dishes cost $$$! It's a matter of economy.
If 2 radio sources, of approximatedly equal strength, are separated in the sky in E-W direction by an angle about $\frac{\lambda}{10d}$ ($\simeq$ 1.5arcsec), the interferometer will be able to resolve them. Below I sketched the response to 2 nearby sources. I made source #2 somewhat weaker than #1.

You can see that the diameter of the dishes does not enter into this. Also notice that d/D is 32 for $D = 25$m and $d/D = 8$ for $D = 100$m. The influence of D (diffraction) shows up in the





term $(\frac{\sin\beta}{\beta})^2$. This alters the heights of the maxima (though not at zero order). For $D = 25$m, at first order (where $\sin\theta = \lambda/d$), $(\frac{\sin\beta}{\beta})^2 \simeq 0.997$. At second order it is about 0.987. If D were 100m, there would be no change in height at zero order, but there would be a $\simeq 5\%$ reduction at first order as $(\frac{\sin\beta}{\beta})^2 \simeq 0.95$. But none of that would affect the angular resolution of the array.

Notice, however, that the field of view of the array is ONLY dictated by D. It is about $\frac{\lambda}{D}$ radians ($\simeq$ 8arcmin for $D = 25$m).

Due to the rotation of the Earth, the sources move in the sky. Each source will produce its own pattern of maxima (see the figure under part (a)) as they move through the field of view of the array. The two patterns can be resolved if the angular separation of the sources (E-W) is larger than about 1.5 arcsec. 1 arcsec is the angle at which you see a dime at a distance of about 2.3 km, this is about 1/1800 of the diameter of the sun and the moon.