PH4606 - Lecture 2

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1   Harmonic Plane Waves

In the following we will consider a constant speed of sound and start with the description of a plane wave propagation. Planar waves have a constant amplitude and phase perpendicular to the direction of propagation. Thus if the wave moves in the x-plane we have:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \quad . \tag{2.1}$$

The complex solution to the harmonic wave equation is

$$p = A\,e^{i(\omega t - kx)} + B\,e^{i(\omega + kx)} \quad . \tag{2.2}$$

Using the linear Euler Eq. (1.11) we can obtain the particle velocity in a plane wave as

$$\mathbf{u} = u\,\vec{e}_1 = \left[\frac{A}{\rho_0 c}e^{i(\omega t - kx)} - \frac{B}{\rho_0 c}e^{i(\omega t + kx)}\right]\vec{e}_1 \tag{2.3}$$

Please note that the constants A and B, pressures and velocities are now all complex. We can separate the wave travelling in positive x-direction from the the wave travelling in negative x-direction and designate them with the subscript $+$ and $-$, respectively.

The wave travelling in positive x-direction is

$$p_+ = Ae^{i(\omega t - kx)} \tag{2.4}$$

while in negative x-direction is

$$p_- = Be^{i(\omega t + kx)} \tag{2.5}$$

These two waves can be formally written for the other acoustic variables:

$$u_\pm = \pm\frac{p_\pm}{\rho_0 c} \tag{1}$$

$$s_\pm = \frac{p_\pm}{\rho_0 c^2} \tag{2}$$

$$\Phi_\pm = -\frac{p_\pm}{i\omega\rho_0} \tag{2.8}$$

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Plane waves travelling in an arbitrary direction can be written as

$$p = Ae^{i(\omega t - k_x x - k_y y - k_z z)} \tag{2.9}$$

If we insert Eq. (2.9) into the wave equation, Eq. (1.17) we obtain the condition

$$\left(\frac{\omega}{c}\right)^2 = k_x^2 + k_y^2 + k_z^2 \quad . \tag{2.10}$$

Now we can introduce the propagation vector, $\mathbf{k}$ of the wave as

$$\mathbf{k} \equiv k_x \mathbf{e_1} + k_y \mathbf{e_2} + k_z \mathbf{e_3} \tag{2.11}$$

with

$$|\mathbf{k}| = \frac{\omega}{c} \quad . \tag{2.12}$$

Thus using the position vector $\mathbf{r} = x\mathbf{e_1} + y\mathbf{e_2} + z\mathbf{e_3}$ we can rewrite the plane wave solution, Eq. (2.9), as

$$p = Ae^{i(\omega t - \mathbf{k} \mathbf{r})} \quad . \tag{2.13}$$

The propagation vector points in the direction of wave propagation which can be simply shown. Surfaces of constant phase are defined by the scalar product $\mathbf{k} \cdot \mathbf{r} = \text{const}$. The vector $\nabla(\mathbf{k} \cdot \mathbf{r})$ is a vector in the normal direction to the constant phase surface. But $\mathbf{k} = \nabla(\mathbf{k} \cdot \mathbf{r})$, thus $\mathbf{k}$ is pointing normal to the plane of constant phase and thus in the direction of propagation.

1.1 Example

Let a plane wave have a constant phase parallel to the z-axis, thus the wave travels in the xy-plane as sketched in Fig. 2.1. Formally the surface of constant phase is $\mathbf{k} \cdot \mathbf{r} = 0$; thus if the phase is independent of z, $\mathbf{k}$ can only have k_x and k_y components. We can thus write Eq. (2.9) as

$$p = Ae^{i(\omega t - k_x x - k_y y)} \tag{2.14}$$

and the equation for the surface of constant phase is

$$k_x x + k_y y = \text{const.} \tag{2.15}$$

or

$$y = -\frac{k_x}{k_y} x + \text{const.} \quad . \tag{2.16}$$

Equation (2.16) is line with a slope $-k_x/k_y$. The surfaces are thus oriented as sketched in Fig. 2.1.

Figure 2.1

Now let's study this wave in the x-direction while $y = 0$

$$p = Ae^{i(\omega t - k_x x)} \tag{2.17}$$

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where $k_x = 2\pi/\lambda_x$ with λ_x being the apparent wavelength in x-direction. Note that this wavelength is larger than the wavelength in $\vec{k}$-direction. We can relate λ_x with the help of Fig. 1 to $\cos\phi = \lambda/\lambda_x$ and thus $k_x = k\cos\phi$. Applying the same arguments in the y-direction gives

$$\mathbf{k} = k\cos\phi\,\mathbf{e}_1 + k\sin\phi\,\mathbf{e}_2 \quad . \tag{2.18}$$

Thus an harmonic plane wave in 2-dimensions propagating under an angle ϕ to the x-axis can be written as

$$p = Ae^{i(\omega t - kx\cos\phi - ky\sin\phi)} \tag{2.19}$$

```python
## Simulation of a 2-dimensional wave

%matplotlib notebook
import math as m
import numpy #array operations
import matplotlib.pyplot as plt #plotting
from ipywidgets import widgets #for the widgets
#from ipykernel.client import display
from IPython import display #for continous display
#from PIL import Image #to export images

nimg=0

def savemyimage(visual):
    global nimg
    visual = (visual +2.)/4.
    #result = Image.fromarray((visual * 255).astype(numpy.uint8))
    #result.save('out{:03d}.bmp'.format(nimg))
    nimg=nimg+1

def plotwave(u,time,px,py,pp,pt):
    plt.figure(1)
    plt.clf()
    plt.subplot2grid((4,4),(0,0), colspan = 4, rowspan = 3)
    plt.imshow(u, origin='upper', extent=[0., 2., 0., 2.], vmax=2, vmin=-2) #plot the wave field
    plt.text(0.1,1.8,"time {0:.5f}".format(time)) #annotate the time
    plt.plot(w_probex.value,1.,'o') #position of probe
    plt.subplot2grid((4,4),(3,0), colspan = 4)
    plt.plot(pt,pp) #plot the pressure at the probe
    plt.gca().set_ylim([-2,2])
    display.clear_output(wait=True)
    display.display(plt.gcf())

def solvewave(b):
    tabs.visible=False
    #computational domain
    nx = ny = 381
    size=2. #size of the domain
    #parameters of the wave
    c = 5. #speed of sound
    l=w_wavelength.value #wavelength
    nu=c/l #frequency
    omega=nu*2.*m.pi #angular frequency
    duration=w_sourceduration.value/nu #duration of source
    #position
    emissionlength=(w_sizeemit.value/100.)*nx
    startx=int(nx/2-emissionlength/2)
    endx=int(nx/2+emissionlength/2)
```

```python
47
48      #further variables
49      dx = size/(nx-1)
50      CFL=0.1 #CFL number <1
51      dt = CFL*dx/c
52      nt=int(w_simduration.value/dt) #number of time steps
53      if w_position.value=='Left':
54          sourcepos=0
55      else:
56          sourcepos=int(nx/2)
57
58      #arrays for measuring the pressure at a position
59      pt=numpy.arange(nt+1)*dt
60      pp=numpy.zeros(nt+1)
61      px=int(w_probex.value*(nx-1)/2.)
62      py=int(ny/2)
63
64      #every xx times over the total nt timesteps an output should be generated
65      output=map(int,list(numpy.linspace(1,nt,int(nt/50))))
66
67      u  = numpy.zeros((nx,ny)) #pressure at t
68      un = numpy.zeros((nx,ny)) #pressure at t-dt
69      unn= numpy.zeros((nx,ny)) #pressure at t-2*dt
70
71      row, col = u.shape
72      #Assign initial conditions, for a sine wave
73      un[startx:endx,0]=0.    #amplitude is sin(omega*t) with t=0
74      unn[startx:endx,0]=1.   #velocity  is cos(omega*t) with t=0
75
76      C=c*c*dt*dt/dx/dx
77
78      plt.figure(1, figsize=(8, 8), dpi=300)
79
80      for n in range(nt+1): ##loop across number of time steps
81          #this line computes the finite differences of the wave equation
82          u[1:-1,1:-1]=2.*un[1:-1,1:-1]-unn[1:-1,1:-1]+C*(un[1:-1,:-2]+\
83                          un[:-2,1:-1]+un[2:,1:-1]+un[1:-1,2:]-4.*un[1:-1,1:-1])
84
85          #hard reflective boundary conditions
86          u[0,:]  = u[1,:]
87          u[-1,:] = u[-2,:]
88          u[:,0]  = u[:,1]
89          u[:,-1] = u[:,-2]
90
91          #pressure source
92          #if float(n*dt<duration):
93          u[startx:endx,sourcepos]=m.sin(omega*n*dt)**2*float(n*dt<duration)
94
95          pp[n]=u[py,px]
96
97          #save values for the time derivative
98          unn=un.copy() #n-1 time steop
99          un=u.copy()   #n time step
100
101         if (n in output):
102             plotwave(u,n*dt,px,py,pp,pt)
103             if (w_saveplots.value):
104                 savemyimage(u)
105
```
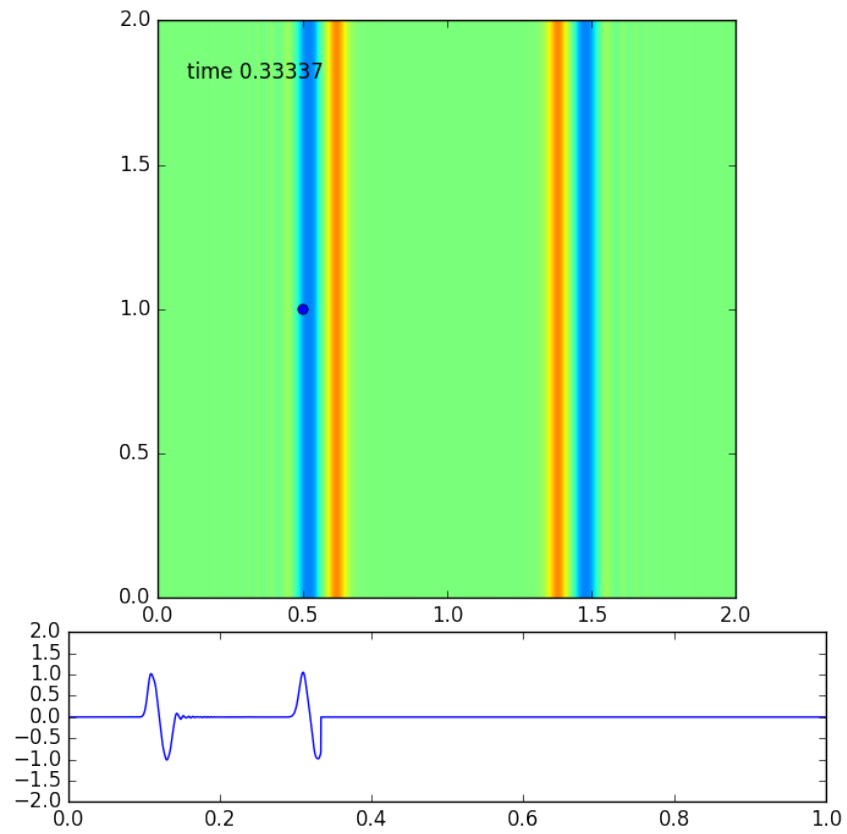
Figure 1:

```
106    #and plot the last figure
107    plotwave(u,n*dt,px,py,pp,pt)
108    tabs.visible=True
```

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