<u>Introduction to Sound</u>

Acoustics – is the physics of sound

waves – are caused by an influence or disturbance initiated at some point and transmitted or propagated to another point in a predictable manner governed by the physical properties of the elastic medium through which the disturbance is transmitted.

sound waves are longitudinal waves. ie. the particles move in the direction of the wave motion.

propagation of sound waves involves the transfer of energy through space.

sound waves spread out in all directions from the source and may be <u>reflected</u>, <u>refracted</u>, <u>scattered</u>, <u>diffracted</u>, <u>interfered</u> and <u>absorbed</u>.

A medium is required for the propagation of sound waves, the speed of which depends on the density and temperature of the medum.

Speed of sound is the speed of propagation of sound waves through the given medium.

the speed of sound in air is

$$c = \sqrt{\gamma P/\rho} \ \ m/sec$$

γ = ratio of the specific heat of air at a constant pressure to that at constant volume

P = pressure in newtons/m^2

ρ = density in kg/m^3

so @ room Temp & std atm pressure

$c = 343$ m/sec & increases ~ 0.6 m/sec for each degree centigrade rise

speed of sound in air is independent of changes in barometric pressure, frequency and wavelength but is directly proportional to absolute Temp.

$$c_1/c_2 = \sqrt{T_1/T_2}$$

No. 5505 Engineer's Computation Pad

Speed of sound in solids having a large cross-sectional areas is

$$c = \sqrt{\frac{Y(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \ \frac{m}{sec}$$

~~where~~ Y = Young's modulus of elasticity $\left(\frac{nT}{m^2}\right)$

ρ = density $\left(\frac{kg}{m^3}\right)$

μ = Poisson's ratio

when the dimension of the cross section is small compared to the wave length the lateral effect in Poisson's ratio can be neglected

$$\Rightarrow \quad c = \sqrt{\frac{Y}{\rho}} \ \frac{m}{sec}$$

the speed of sound in fluids is

$$c = \sqrt{\frac{B}{\rho}} \ \frac{m}{sec}$$

The bulk modulus of a fluid is analogous to the modulus of elasticity of a solid.

B = Bulk modulus in $\frac{nT}{m^2}$

ρ = density in $\frac{kg}{m^3}$

Home work:

1) Calculate the speed of sound in air at 20°C and standard atmospheric pressure (List all values and where the information was obtained from)

2) The bulk modulus of water is $B = 2.1(10)^9 \frac{nt}{m^2}$ Find the speed of sound in water.

3) Young's modulus of copper is $12.2(10)^{10} \frac{nt}{m^2}$ and the density of copper is $8900 \frac{kg}{m^3}$ calculate the speed of sound in copper.

4) Prove that the speed of sound in air is proportional to the square root of the absolute temperature.

see Pg 50 waite

In underwater acoustics, the ocean is a waveguide and the speed of sound plays the same role as the index of refraction does in optics.

Sound speed is normally related to density & compressibility.

In the ocean density is related to static pressure (which increase with depth), salinity and Temperature (which varies significantly in the upper mixing layer).

∴ the speed of sound in the ocean is an increasing function of Temp, salinity & Pressure.

A simplified expression by (Clay & Medwin 1977)

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.10T)(S-35) + 0.016z$$

Encyclopedia of Applied physics

T = Temp S = Salinity z = depth

For most cases this is sufficiently accurate.

Figure 1 (illustrates a Typical set of sound speed profiles indicating greatest variability near the surface as a function of season and Time of day

Formulas for sound velocity at zero depth or atm pressure

Kuwahara (1939)

$$c = 1,445.5 + 4.664\,T - 0.0554\,T^2 + 1.307(S-35) + \ldots$$

Del Grosso (1952)

$$c = 1448.6 + 4.618\,T - 0.0523\,T^2 + 1.25(S-35) + \ldots$$

Wilson (1960)

$$c = 1449.2 + 4.623\,T - 0.0546\,T^2 + 1.391(S-35) + \ldots$$

(Principles of Underwater Sound for Engineers
R.J. Urick pg 94)

S = salinity, parts per thousand

T = temperature °C

Uses of sound:

Sonar - Passive (use sound radiated by the target)
- Active (sound is purposely generated)

Communication

Fish finder
Depth finder

Sub bottom Profiling

Side scan

Sensing - T_0
- Salinity
- Pressure

Doppler Sonar
- speed
- current profiling

Diver location

Navigation Aids - Beacons
- Transponder

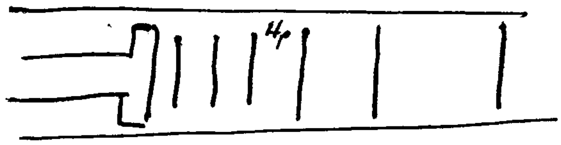
Control

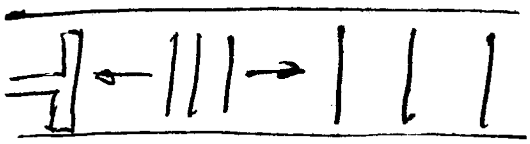
(Power point Presentation)

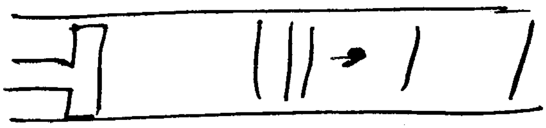
Sound - Pressure - Waves

what is a sound wave?

Low Pressure







Speed of the wave is some function of the fluid properties.

but the speed of particles is a function of the piston speed

How do we measure this?

use pressure

Threshold of Hearing 1×10^{-5} Pa $\left(\frac{N}{m^2}\right)$

of Pain 1×10^{2} Pa

this is non-intuitive so we use a log scale known as the decibel scale. this Relates ~~SOUND PRESSURE LEVEL (SPL)~~ the quantities encountered in the acoustical environment (sound power, intensity and pressure) to some standard reference.

- Decibel (db) is a dimensionless unit for expressing the ratio of two powers, which can be acoustical, mechanical, or electrical.

The number = 10 * the logarithmic to the base 10 of the power ratio.

One bel = 10 decibels

so the <u>Sound Power Level</u> PWL is

$$PWL = 10 \log\left(\frac{W}{W_0}\right) \text{ db re } W_0 \text{ watts}$$

W = power in watts

W_0 = reference power (watts)

re = refer to the reference power W_0

for standard power reference $W_0 = 10^{-12}$ watt/m^2 air borne sounds or 20 μPa

$$PWL = (10 \log W + 120) \text{ db}$$

water ~~... 10^5 ...~~

$P_0 = 6.76 \times 10^{-19}$ W/m^2 or 1 μPa

spl re 1 μbar + 100 = spl re 1 μPa

spl re 0.0002 μbar − 74 = spl re 1 μbar

spl re 0.0002 μbar + 25 = spl re 1 μPa

INTRODUCTION

Sound waves are produced when air is disturbed, and travel through a three-dimensional space commonly as progressive longitudinal sinusoidal waves. Assuming no variation of pressure in the y or z direction, we can define *plane acoustic waves* as one-dimensional free progressive waves traveling in the x direction. The wavefronts are infinite planes perpendicular to the x axis, and they are parallel to one another at all time.

In fact, when a small body is oscillating in an extended elastic medium such as air, the sound waves produced will spread out in widening spheres instead of planes. The longitudinal wave motion of an infinite column of air enclosed in a smooth rigid tube of constant cross-sectional area closely approximates plane acoustic wave motion.

WAVE EQUATION

In the analysis of plane acoustic wave motion in a rigid tube, we make the following assumptions: (*a*) zero viscosity, (*b*) homogeneous and continuous fluid medium, (*c*) adiabatic process, and (*d*) isotropic and perfectly elastic medium. Any disturbance of the fluid medium will result in the motion of the fluid along the longitudinal axis of the tube, causing small variations in pressure and density fluctuating about the equilibrium state. These phenomena are described by the *one-dimensional wave equation*

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

where $c = \sqrt{B/\rho}$ is the speed of wave propagation, B the bulk modulus, ρ the density, and u the instantaneous displacement.

Since this partial differential equation of motion for plane acoustic waves has exactly the same form as those for free longitudinal vibration of bars and free transverse vibration of strings, practically everything deduced for waves in strings and bars is valid for plane acoustic waves.

The general solution for the one-dimensional wave equation can be written in *progressive waves* form

$$u(x,t) = f_1(x-ct) + f_2(x+ct)$$

which consists of two parts: the first part $f_1(x-ct)$ represents a wave of arbitrary shape traveling in the positive x direction with velocity c, and the second part $f_2(x+ct)$ represents a wave also of arbitrary shape traveling in the negative x direction with velocity c. In *complex exponential* form, the general solution can be written as

$$u(x,t) = Ae^{i(\omega t - kx)} + Be^{i(\omega t + kx)}$$

where $k = \omega/c$ is the wave number, $i = \sqrt{-1}$, and A and B are arbitrary constants (real or complex) to be evaluated by initial conditions. In *sinusoidal* sine and cosine series, the general solution is

$$u(x,t) = \sum_{i=1,2,\ldots}^{\infty} \left(A_i \sin\frac{p_i}{c}x + B_i \cos\frac{p_i}{c}x\right)(C_i \sin p_i t + D_i \cos p_i t)$$

where A_i and B_i are arbitrary constants to be evaluated by boundary conditions, C_i and D_i are arbitrary constants to be evaluated by initial conditions, and p_i are the natural frequencies of the system. (See Problems 2.1-2.6.)

WAVE ELEMENTS

Plane acoustic waves are characterized by three important elements: particle displacement, acoustic pressure, and density change or condensation.

Particle displacements from their equilibrium positions are amplitudes of motion of small constant volume elements of the fluid medium possessing average identical properties, and can be expressed as

$$u(x,t) = Ae^{i(\omega t - kx)} + Be^{i(\omega t + kx)}$$

or

$$u(x,t) = A\cos(\omega t - kx) + B\cos(\omega t + kx)$$

Acoustic pressure p is the total instantaneous pressure at a point minus the static pressure. This is often referred to as excess pressure. The *effective sound pressure* p_{rms} at a point is the *root mean square* value of the instantaneous sound pressure over a complete cycle at that point. Thus

$$p = -\rho c^2 \frac{\partial u}{\partial x} = i\rho c\omega(Ae^{i(\omega t - kx)} - Be^{i(\omega t + kx)})$$

or

$$p = -\rho c\omega A\sin(\omega t - kx) + \rho c\omega B\sin(\omega t + kx)$$

Density change is the difference between the instantaneous density and the constant equilibrium density of the medium at any point, and is defined by the *condensation* s at such point as

$$s = \frac{\rho - \rho_0}{\rho_0} = -\frac{\partial u}{\partial x} = ikAe^{i(\omega t - kx)} - ikBe^{i(\omega t + kx)}$$

When plane acoustic waves are traveling in the positive x direction, it is clear that particle displacement lags particle velocity, condensation and acoustic pressure by 90°. On the other hand, when plane acoustic waves are traveling in the negative x direction, acoustic pressure and condensation lag particle displacement by 90° while particle velocity leads it by 90°. (See Problems 2.7-2.9.)

SPEED OF SOUND

The speed of sound is the speed of propagation of sound waves through the given medium. The speed of sound in air is

$$c = \sqrt{\gamma p/\rho} \text{ m/sec}$$

where γ is the ratio of the specific heat of air at constant pressure to that at constant volume, p is the pressure in newtons/m², and ρ is the density in kg/m³. At room temperature and standard atmospheric pressure, the speed of sound in air is 343 m/sec and increases approximately 0.6 m/sec for each degree centigrade rise. The speed of sound in air is independent of changes in barometric pressure, frequency and wavelength but is directly proportional to absolute temperature, i.e.

$$c_1/c_2 = \sqrt{T_1/T_2}$$

The speed of sound in solids having large cross-sectional areas is

$$c = \sqrt{\frac{Y(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \text{ m/sec}$$

where Y is the Young's modulus of elasticity in nt/m², ρ the density in kg/m³, and μ Poisson's ratio. When the dimension of the cross section is small compared to the wavelength, the lateral effect considered in Poisson's ratio can be neglected and the speed of sound is simply

$$c = \sqrt{Y/\rho} \text{ m/sec}$$

The speed of sound in fluids is

$$c = \sqrt{B/\rho} \text{ m/sec}$$

where B is the bulk modulus in nt/m² and ρ is the density in kg/m³. (See Problems 2.10-2.13.)

ACOUSTIC INTENSITY

Acoustic intensity I of a sound wave is defined as the average power transmitted per unit area in the direction of wave propagation:

$$I = \frac{p_{\text{rms}}^2}{\rho c} \text{ watts/m}^2$$

where p_{rms} is the effective (root mean square) pressure in nt/m², ρ is the density in kg/m³, and c is the speed of sound in m/sec.

At room temperature and standard atmospheric pressure, $p_{\text{rms}} = 0.00002$ nt/m², $\rho = 1.21$ kg/m³, $c = 343$ m/sec, and so acoustic intensity for airborne sounds is approximately 10^{-12} watt/m². (See Problems 2.14-2.18.)

SOUND ENERGY DENSITY

Sound energy density is energy per unit volume in a given medium. Sound waves carry energy which is partly potential due to displacement of the medium and partly kinetic arising from the motion of the particles of the medium. If there are no losses, the sum of these two energies is constant. Energy losses are supplied from the sound source.

The instantaneous sound energy density is

$$E_{\text{ins}} = \rho \dot{x}^2 + \frac{p_0 \dot{x}}{c} \text{ watt-sec/m}^3$$

and the average sound energy density is

$$E_{\text{av}} = \tfrac{1}{2}\rho \dot{x}^2 \text{ watt-sec/m}^3$$

where ρ is the instantaneous density in kg/m³, p_0 is the static pressure in nt/m², $\dot{x}$ is particle velocity in m/sec, and c is the speed of sound in m/sec. (See Problems 2.19-2.20.)

SPECIFIC ACOUSTIC IMPEDANCE

Specific acoustic impedance z of a medium is defined as the ratio (real or complex) of sound pressure to particle velocity:

$$z = p/v \text{ kg/m}^2\text{-sec or rayls}$$

where p is sound pressure in nt/m², and v is particle velocity in m/sec.

For harmonic plane acoustic waves traveling in the positive x direction,

$$z = \frac{-\rho c \omega A}{-\omega A} = \rho c \text{ rayls}$$

and for harmonic plane acoustic waves traveling in the negative x direction,

$$z = \frac{-\rho c \omega A}{\omega A} = -\rho c \text{ rayls}$$

where ρ is the density in kg/m³, c is the speed of sound in m/sec, and ρc is known as the *characteristic impedance* or *resistance* of the medium in *rayls*. At standard atmospheric pressure and 20°C, for example, the density of air is 1.21 kg/m³, the speed of sound is 343 m/sec, and so the characteristic impedance of air is 1.21(343) or 415 rayls. For distilled water at standard atmospheric pressure and 20°C, the density is 998 kg/m³ and the speed of sound is 1480 m/sec; hence its characteristic impedance is $1.48(10)^6$ rayls.

For standing waves, the specific acoustic impedance will vary from point to point in the x direction. In general, it is a complex ratio

$$z = r + ix \text{ rayls}$$

where r is the *specific acoustic resistance*, x is the *specific acoustic reactance* and $i = \sqrt{-1}$.

SOUND MEASUREMENTS

Because of the very wide range of sound power, intensity and pressure encountered in our acoustical environment, it is customary to use the logarithmic scale known as the *decibel scale* to describe these quantities, i.e. to relate the quantity logarithmically to some standard reference. *Decibel* (abbreviated db) is a dimensionless unit for expressing the ratio of two powers, which can be acoustical, mechanical, or electrical. The number of decibels is 10 times the logarithm to the base 10 of the power ratio. One *bel* is equal to 10 decibels. Thus *sound power level* PWL is defined as

$$\text{PWL} = 10 \log (W/W_0) \text{ db} \quad \text{re } W_0 \text{ watts}$$

where W is power in watts, W_0 is the reference power also in watts, and re = refer to the reference power W_0. For standard power reference $W_0 = 10^{-12}$ watt,

$$\text{PWL} = (10 \log W + 120) \text{ db}$$

The acoustical power radiated by a large rocket, for example, is approximately 10^7 watts or 190 db. For a very soft whisper, the acoustical power radiated is 10^{-10} watt or 20 db.

Sound intensity level IL is similarly defined as

$$\text{IL} = 10 \log (I/I_0) \text{ db} \quad \text{re } I_0 \text{ watts/m}^2$$

For standard sound intensity reference $I_0 = 10^{-12}$ watt/m^2,

$$\text{IL} = (10 \log I + 120) \text{ db}$$

Sound pressure level SPL is thus defined as

$$\text{SPL} = 20 \log (p/p_0) \text{ db} \quad \text{re } p_0 \text{ nt/m}^2$$

For standard sound pressure reference $p_0 = 2(10)^{-5}$ nt/m^2 or 0.0002 microbar,

$$\text{SPL} = (20 \log p + 94) \text{ db}$$

In vibration measurements, the *velocity level* VL is similarly defined as

$$\text{VL} = 20 \log (v/v_0) \text{ db} \quad \text{re } v_0 \text{ m/sec}$$

where $v_0 = 10^{-8}$ m/sec is the standard velocity reference. The *acceleration level* AL is

$$\text{AL} = 20 \log (a/a_0) \text{ db} \quad \text{re } a_0 \text{ m/sec}^2$$

where $a_0 = 10^{-5}$ m/sec^2 is the standard acceleration reference. (See Problems 2.21-2.29.)

RESONANCE OF AIR COLUMNS

Acoustic resonance of air columns is tuned response where the receiver is excited to vibrate by sound waves having the same frequency as its natural frequency. Resonant response depends on the distance between sound source and the receiver, and the coupling medium between them. It is, in fact, an exchange of energy of vibration between the source and the receiver.

The Helmholtz resonator makes use of the principle of air column resonance to detect a particular frequency of vibration to which it is accurately tuned. It is simply a spherical container filled with air, and having a large opening at one end and a much smaller one at the opposite end. The ear will hear amplified sound of some particular frequency from the small hole when sound is directed through the larger hole.

Half wavelength resonance of air columns will be observed when the phase change on reflection is the same at both ends of the tube, i.e. either two nodes or two antinodes. The effective lengths of air column and its resonant frequencies are

$$L = i\lambda/2, \quad f = c/\lambda = ic/2L, \quad i = 1, 2, \ldots$$

where λ is the wavelength and c is the speed of sound.

Quarter wavelength resonance of air columns will be observed when there is no change in phase at one end of a stationary wave but 180° phase change at the other end. The effective lengths of air column and its resonant frequencies are

$$L = \lambda(2i-1)/4, \quad f = c(2i-1)/4L, \quad i = 1, 2, 3, \ldots$$

In general, an open end of a tube of air is an antinode, and a closed end a node. (See Problems 2.30-2.37.)

DOPPLER EFFECT

When a source of sound waves is moving with respect to the medium in which waves are propagated, or an observer is moving with respect to the medium, or both the source and the observer have relative motion with respect to each other and to the medium, the frequency detected by the observer will be different from the actual frequency of the sound waves emitted by the source. This apparent change in frequency is known as the *Doppler effect*.

The observed frequency of a sound depends essentially on the number of sound waves reaching the ear per second, and is given by

$$f' = (c-v)f/(c-u) \text{ cyc/sec}$$

where f' is the observed frequency, c the speed of sound, v the speed of the observer relative to the medium, and u the speed of the source. When the source and observer are approaching each other, the observed frequency is increased; while if they are receding from each other, the observed frequency is lowered. (See Problems 2.38-2.41.)

ref $10^{-12}W$ = $20\mu Pa$

Acoustic power of a large rocket $\simeq 10^{7}$ watts or 190 db

soft whisper $\simeq 10^{-10}$ watts or 20 db

Sound Intensity level (IL) is similarly defined

$$IL = 10 \log \frac{I}{I_o} \text{ db re } I_o \ \frac{\text{watts}}{m^2}$$

I = Acoustic intensity

Acoustic Intensity (I) of a sound wave is defined as the average power transmitted per unit area in the direction of wave propagation

$$I = \frac{\mathbb{P}}{A}$$

$$I = \frac{\mathbb{P}}{4\pi r^2} \quad \text{sperical source}$$

$\mathbb{P}$ = Acoustic power (watts) or $\frac{ergs}{sec}$

$A = 4\pi r^2$ area of the spheres of radius r through which the acoustic energy must flow

$$I = \frac{\text{watts}}{m^2} \text{ or } \frac{ergs}{sec/cm^2}$$

1 watt = 10^7 ergs/sec

$$\mathbb{P} = \frac{p^2 A}{\rho c}$$

p is the sound pressure

$p = P_{RMS}$ (Root mean square)

$$I = \frac{P_{RMS}^2}{\rho c} \ \frac{\text{watts}}{m^2}$$

$$\mathbb{P} = \frac{10^{-7}\pi r^2 p^2}{\rho c} \text{ watts}$$

$$I = \frac{1}{2}\rho c \omega^2 A^2$$

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P_{RMS} is the effective (root mean square) pressure in $\frac{nT}{m^2}$.

ρ = density in $\frac{kg}{m^3}$

c = speed of sound in $\frac{m}{s}$

@ room Temp & std atm pressure, $P_{RMS} = 0.00002 \frac{nT}{m^2}$

$\rho = 1.21 \frac{kg}{m^3}$, $c = 343 \frac{m}{sec}$, so the acoustic intensity for airborne sounds is $\approx 10^{-12} \frac{watt}{m^2}$

so for a standard sound intensity reference

$I_0 = 10^{-12} \frac{watt}{m^2}$

$$IL = (10 \log I + 120)\ db$$

Homework

Compare the intensities of sound in air and in water for (a) the same acoustic pressure and (b) the same frequency and displacement amplitude

$\rho_{air} = ?$ characteristic impedance of air is $\rho c = ?$ rayls

$c_{air} = ?$

$\rho_{H_2O} = ?$ characteristic impedance of H_2O

$c_{H_2O} = ?$ $\rho c = ?$ rayls (see 9a)

P_{eff} = effective pressure

Sound Pressure Level = SPL

$$SPL = 10 \log \left(\frac{P_{eff}^2}{P_0^2} \right) = 20 \log \left(\frac{P_{eff}}{P_0} \right) \text{ db} \quad \text{re } P_0 \frac{nT}{m^2}$$

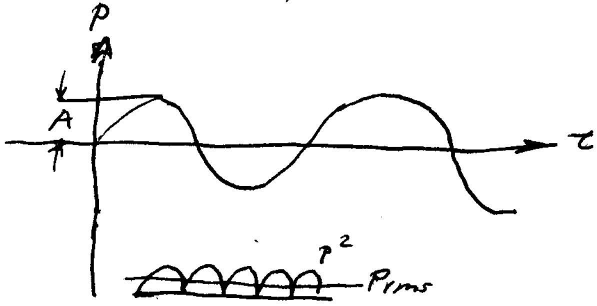
$$P_0 = 2(10)^{-5} \frac{nT}{m^2} \text{ or } 0.0002 \text{ microbar}$$

$$SPL = (20 \log P + 94) \text{ db}$$

P_{eff}^2 or P_{rms}^2 Time average pressure

$$p_{eff}^2 = \frac{1}{T} \int_0^T p^2(t)\, dt$$

EG. For a simple harmonic wave



$$P_{rms}^2 = \frac{1}{T} \int_0^T A^2 \sin^2(\omega t)\, dt$$

$$P_{rms}^2 = \frac{A^2}{2} \quad P_{rms} = \frac{A}{\sqrt{2}} \text{ or } P_{eff}$$

Go to 10

P_{ref} air $= 20\ \mu Pa$

P_{ref} water $= 1\ \mu Pa$ (standard)

$$SPL = 10 \log\left(\frac{P_{rms}^2}{P_{ref}^2}\right)$$

If $P_{rms} = P_{ref}$ $\quad SPL = 10 \log(1)$

$SPL = 0$ db

what happens if we add harmonic signals?

① $A \sin \omega_1 t$

② $B \sin(\omega_2 t + \phi)$ phase dif

$$P(t) = A \sin \omega_1 t + B \sin(\omega_2 t + \phi)$$

1st case

So ① is the reference

what is the SPL increase

$\omega_2 = \omega_1$

$A = B$

$\phi = 0$

$P_{ref}(t) = A \sin(\omega t)$ $\qquad \bar{P}^2 = P_{eff}^2$

$p(t) = 2A \sin(\omega t)$

$$\bar{p}^2 = \frac{1}{T}\int_0^T 2^2 A^2 \sin^2(\omega t)\, dt$$

$$\overline{p^2} = 4\frac{A^2}{2}$$