PM7

SOUND

Some claim that pianists are human,
And quote the case of Mr Truman.
St Saens, upon the other hand,
Considered them a scurvy band.
Ape-like they are, he said, and simian,
Instead of normal men and wimian.

OBJECTIVES

Aims

In this chapter you will study the phenomena of sound. You will find that the speed of sound depends on the stiffness and the density of the medium it propagates through. The property *specific acoustic impedance*, of a medium is defined and its role in determining the reflection of sound from boundaries between two media is discussed. The physics involved in the ear and in hearing is discussed.

Minimum Learning Goals

When you have finished studying this chapter you should be able to do all of the following.

1 Explain and use the following terms: *acoustic impedance, specific acoustic impedance, impedance matching, Fourier analysis, Fourier synthesis*.

2 Recall how the acoustic impedance of a medium depends on the bulk modulus and the density of the medium.

3 (i) Recall how the specific acoustic impedance of a medium depends on the bulk modulus and the density of the medium.

(ii) Give a definition of sound power reflection coefficient between two media in terms of the amplitudes of incident and the reflected waves and in terms of the specific acoustic impedances of the two media.

(iii) Describe an experiment to verify these laws.

4 Describe what is meant by an acoustic impedance mismatch; and describe a method by which the problems arising from such a mismatch may be avoided.

5 Describe an experiment to analyze the frequency components present in a musical note or other sound.

6 (i) Draw a schematic diagram of the ear, identifying the following : *outer ear, auditory canal, eardrum (tympanic membrane), ossicles, oval window, cochlea*.

(ii) Draw a schematic diagram of the cochlea identifying the basilar membrane and the nerve cells.

(iii) State the general form of the information processed in the cochlea and sent to the brain.

(iv) Describe how ageing limits the frequency response of the ear.

PRE-LECTURE

Recall the following information from various lectures scattered throughout this course.

(i) The definition of the Bulk Modulus, and Hooke's Law as it applies to substances which are deformed by volume compression stresses.

(ii) In Electrical Circuit Theory there is a theorem called the **power matching theorem**. It concerns the problem of getting energy from a source (battery) to somewhere it can be used (load). In order to get efficient power transfer, it is found that it is necessary for the impedance (resistance) of the load to match the internal resistance of the battery. If either one of these two is much bigger than the other, then only a small fraction of the available energy appears in the load, most is dissipated in the source. This will be discussed in greater detail in the live lecture following this television lecture.

In many, many cases involving the transport of energy from one place to another, the same kind of reasoning will be found to apply. There will be a source and a receiver (load); and there will be property of each which will effectively determine its ability to accept and transmit energy; this will usually be given the name impedance. Then, unless the impedance of the source is roughly the same as the impedance of the receiver, energy will not readily get from one to the other.

(iii) A mathematical discussion of simple harmonic oscillations was given in lecture FE7. For a mass oscillating at the end of a spring, the force is given by Hooke's law pointing to the fact that this kind of oscillation is essentially an elastic phenomenon.

You will recall from that discussion that the frequency of a simple harmonic oscillation was determined by (a) the mass of the object and (b) its spring constant (or alternately its Young's Modulus). Sound consists of elastic vibrations also (pressure oscillations in fact) and you would therefore expect that a mathematical analysis would yield a similar result: viz. that the parameters describing the propagation of sound waves through a medium would also depend on two quantities: the density or the medium, □ and its Bulk Modulus k.

(iv) Also in lecture FE7 you met the concept of **fourier analysis**, the breaking down of a complicated oscillation into a sum of simpler sinusoidal oscillations. Each of these sinusoidal components has an amplitude and a phase.

The inverse problem, that of starting with simple oscillations and combining them into a more complicated shape is called **fourier synthesis**.

LECTURE

It is assumed that you already know a fair bit about sound, particularly how it is generated. We will concentrate on two aspects only: its propagation and its analysis. We do this with specific reference to the EAR and electrical hearing devices.

7-1 ACOUSTIC IMPEDANCE

The ear may be sketched schematically thus:

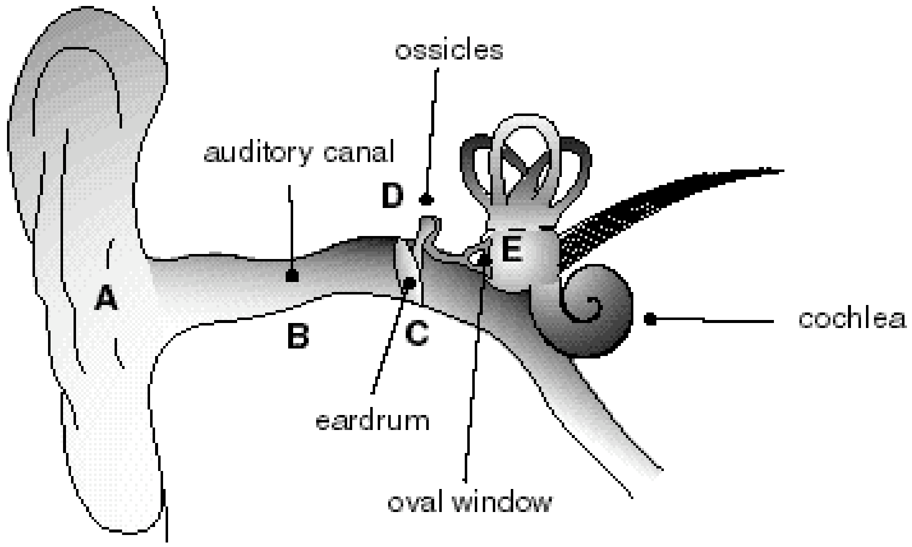

Fig 7.1 Cross-section of the ear

Sound waves impinge on the outer ear (A) and are conducted through the narrowing column of air (B) to the drum (C). There the vibrations of air pressure are translated into mechanical oscillations, which are carried with slight mechanical advantage due to lever action, by the ossicles (D) to another membrane, the oval window (E). Beyond that point the information in the sound is converted into electrical signals to be sent to the brain.

To understand the structure of the outer ear, we must talk in general terms about the propagation of pressure waves through an elastic medium.

Demonstration

A mechanical model of an elastic medium might be:

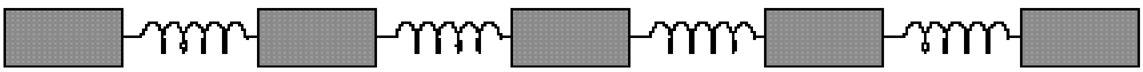

Fig 7.2 A mechanical model of an elastic medium

The speed at which a disturbance will travel down this chain can be seen to depend on

(i) the mass of the object. Clearly the heavier the objects, the more slowly will each mass move after being pushed by its neighbour, and the more slowly will the "wave" propagate.

ii) the strength of the springs. Clearly the stronger the springs, the more quickly will they expand after being compressed, and so the more quickly will the "wave" propagate.

Generalizing to a three dimensional rather than a linear medium, we might expect the speed of sound to increase as the density decreases, and as the bulk modulus increases.The formula is

$$\text{speed of sound:} \quad c = \sqrt{k/\rho}$$

(k is the bulk modulus, ρ is the density.)

Consider now the boundary between two media. What determines how a wave propagates from one to the other?

*An extremely simple mechanical model is a row of billiard balls:

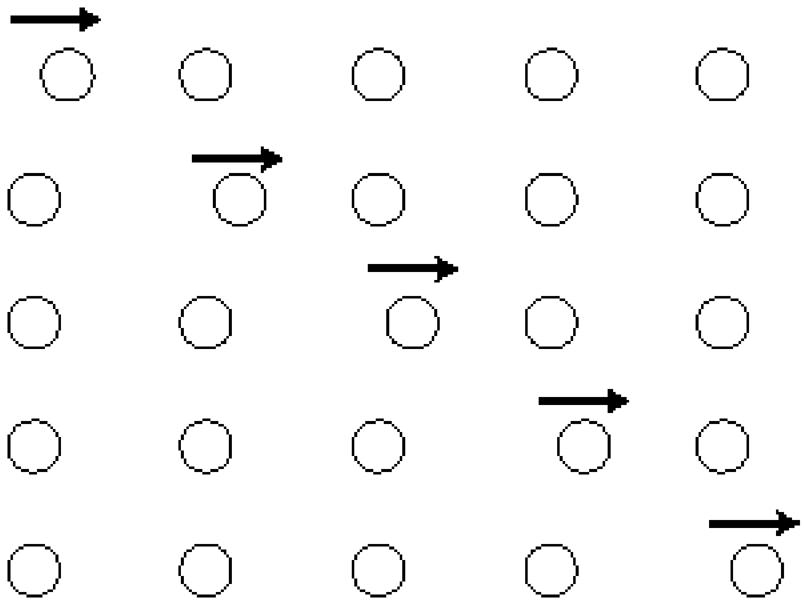

Fig 7.3 A disturbance "propagating" through a row of billiard balls.

The disturbance propagates with no net motion of the medium **only if all balls are absolutely identical**. [Why?]

If any one ball is heavier or lighter than the others, then the disturbance will result in some **reflection** as well as propagation of kinetic energy.

Demonstration

A better mechanical model is again cars and springs.

A disturbance will propagate with no net motion in the medium, only if all cars and all springs are identical. Reflection will occur at any point where there is as CHANGE of either mass or spring strength.

Demonstration

However, an increase in mass can, in part, be compensated for by a decrease in spring strength.

Careful experimentation will show that you can maximize propagation and minimize reflection if you keep the **product** of mass and spring strength constant along the medium.

Generalizing to three dimensions, we define a quantity called the **specific acoustic impedance**, z, by the equation

$$z \equiv \sqrt{k\rho}$$

to serve as an index to tell us whether sound energy can efficiently be transferred from one medium to another.

Clearly we could redefine this quantity (as is more usual) in terms of the velocity of sound, c:

$$z = \rho c$$

The specific acoustic impedance is a property of the medium. A particular acoustic device will be described by a quantity called the **acoustic impedance**, which depends on both the shape and size of the device.

The name impedance comes from the analogy with electrical circuit theory (as described in the pre-lecture material). It may be helpful in understanding this subject to realize that acoustic impedance plays a role analogous in some respects to resistance; and in the same way specific acoustic impedance is analogous to resistivity.

Consider again the ear. Since both the density and bulk modulus of skin are much greater than that of air, the specific impedance of the eardrum is vastly different from that of the outside air. Hence there is an enormous mismatch of specific impedances, and only a tiny fraction of the energy of the sound wave can get from the air into the eardrum. The rest is simply reflected back.

This is a bit of a simplification. As we said before, acoustic impedance depends also on the geometry of the device; and the narrowing of the auditory canal plays a most important role. The impedance of a layer of air near the drum is considerably greater than a layer of air near the outer ear. Crudely speaking, a narrow column of air is more difficult to get moving than completely free air, because of viscous effects at the side of the tube. Its impedance is increased by the narrowness of the tube.

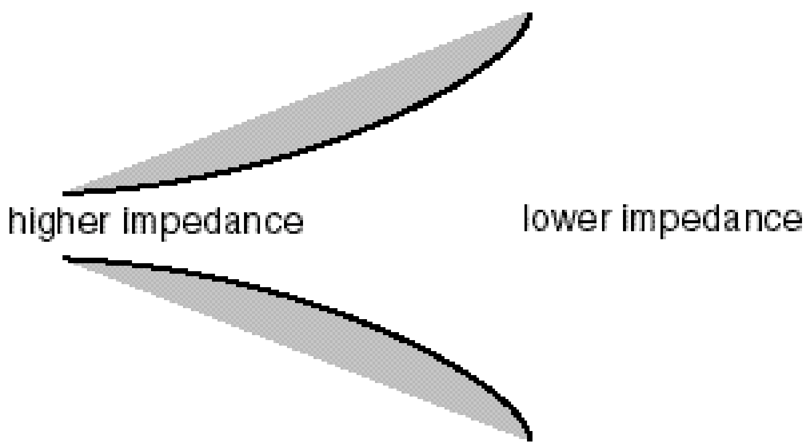

Fig 7.4 Impedance and width of tube

(The use of a horn shape to get impedance matching comes into loudspeaker design, where the problem is to get energy from inside out into the air.)

Nevertheless, the impedance of the air near the drum, and that of the drum itself are still badly mismatched, and most of any sound wave is reflected away.

Demonstration

Clinical measurements of drum impedance feed into the ear a sound of known intensity, and measure the intensity reflected from the drum.

This gives the impedance of the drum (relative to that of air [see post-lecture]. Obviously, for example, if no sound is reflected, the impedance of the drum is exactly the same as that of air.

Since you know the elasticity and density of skin and bone, it should be possible to work out the acoustic impedance of a normal ear and how it is affected if you change the pressure, for example. This is rather an impossible calculation; but standard audiological procedure is to measure the way drum impedance varies with pressure and to compare with a known normal ear. By this means, it is possible to pick up certain specific defects in the drum or the ossicular chair - for example a perforated drum or a calcified ossicular chain.

To sum up: there is an enormous impedance mismatch between the eardrum and the outside air, so you only detect a very small fraction of the energy in any sound wave. From this point of view, the ear is in an inefficient hearing device. Electrical hearing devices for example get over this problem by incorporating an AMPLIFIER as an essential component.

7-2 FOURIER ANALYSIS

Beyond the oval window in the inner ear is the **cochlea**, a snail like structure which, if it could be straightened out, might look in principle like this:

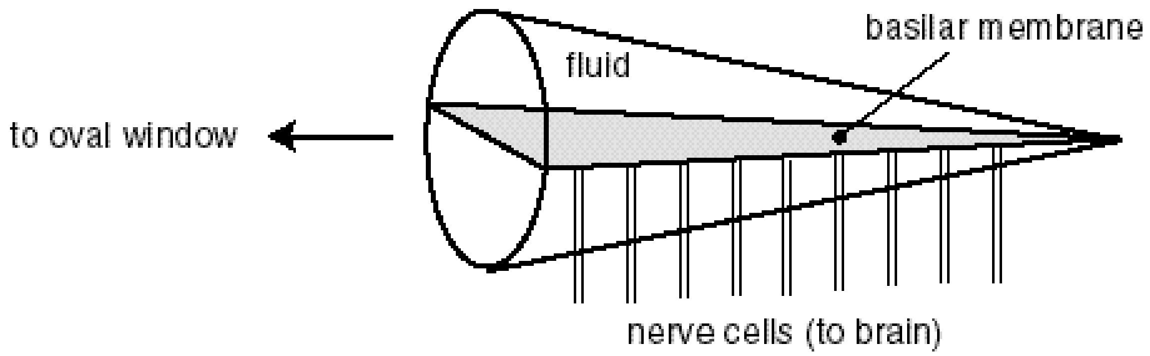

Fig 7.5 A "straightened out" cochlea

Pressure variations in the oval window are transmitted by fluid to the basilar membrane. Because of its geometrical shape, different parts of this membrane resonate with oscillations of different frequencies. Nerve cells connecting this membrane to the auditory nerve, tell the brain which part of the basilar membrane is vibrating - and thus what simple harmonic oscillations are present in the original sound wave.

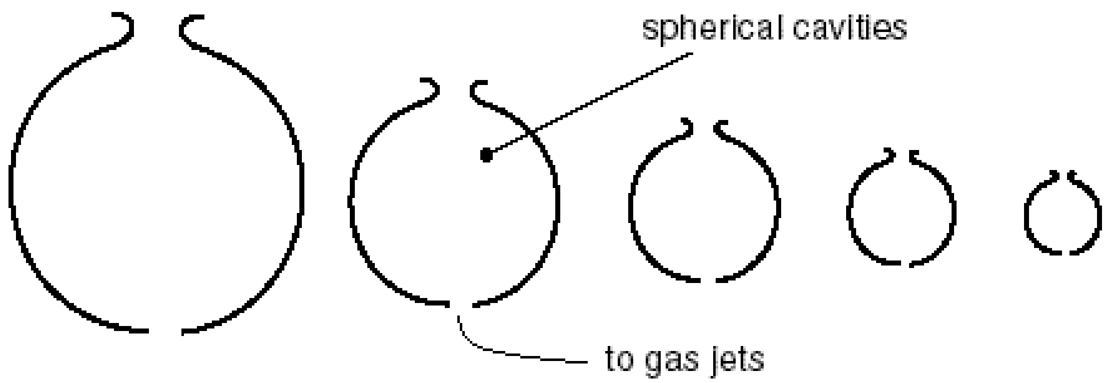

Fig 7.6 Helmholtz Spectrum Analyzer

Demonstration

A musical note of the correct frequency will cause one of these cavities to resonate. The increased amplitude of vibrations thus set up, are made to cause a gas jet to flicker up and down. Which cavity is resonating can then be detected in a rotating mirror system (this apparatus was built circa 1890).

Demonstration

This apparatus is in principle capable of identifying all the harmonies present in any musical note. However, it is too cumbersome to use seriously. Modern spectrum analysis is all done electronically. Sound is fed into a microphone and the result displayed on an oscilloscope screen. You interpret the output thus: for a reasonably pure note you might get something like

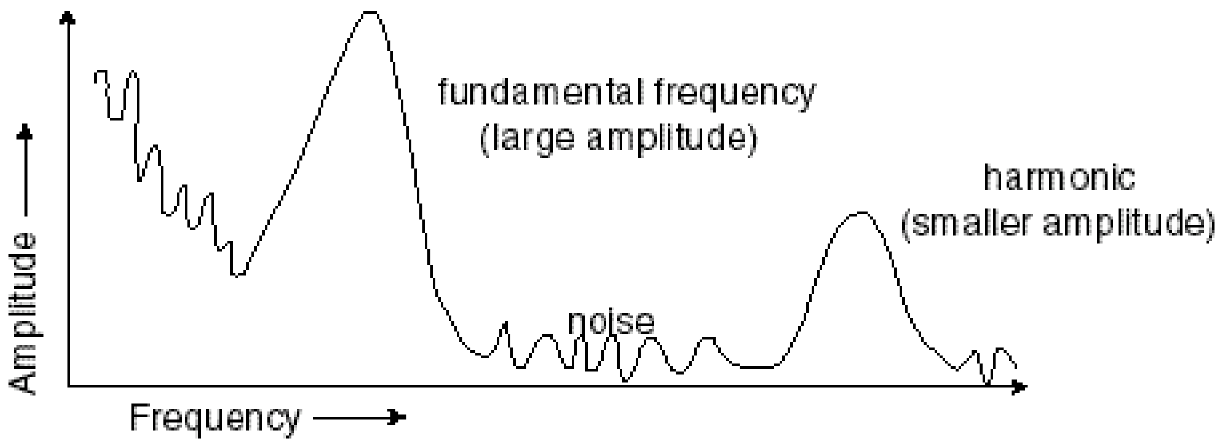

Fig 7.7 Spectrum of sound as seen on a spectrum analyzer screen

[Note: in order to analyze the spectrum accurately the apparatus must listen to the note for some time and "count" how many oscillations occur in that time. That is why you see such a slow rate of scan. The slower the rate the more accurate the analysis.]

*With the aid of a spectrum analyzer you can determine what gives the human voice or various musical instruments their distinctive sounds. It is just a question of what harmonics (or overtones) are present, and in what strength (amplitude).

*In order to get a feeling for the relationship between a sound and its spectrum, just listen to the sounds as they are produced and see if you can correlate the most prominent features of the spectrum you see with what you hear.

[Note: It seems to be the basic philosophy of much modern music that the older instruments have become stale and uninteresting. And indeed the spectrum of one wind instrument for example, is very like that of another. So musicians today are trying to get sounds out of all sorts of unlikely instruments - to produce completely new spectra for the ear to listen to.]

To sum up: the cochlea is a device for translating a series of pressure vibrations into a coded set of electrical signals which the brain uses as a sensory input. And the information going to the brain is of the general form:

(i) what simple harmonic frequencies are present, and

(ii) what their amplitudes are.

That this is a true representation of the ear can be confirmed by two observations.

Demonstration

(i) In some deaf schools, children are taught to speak by getting them to match the oscilloscope pattern of a sound made by the teacher. In the way this technique is usually used, the pattern the child has to reproduce is NOT the frequency spectrum but simply the pressure-time variations. However, you will notice that the teacher has obviously found from experience that it is most effective to change the scale every now and then, thus directing the child's attention to specific harmonics.

[This technique is still not fully developed or accepted; and one suspects that it will not be until it is carried out with complete spectrum analyzers rather than simple oscilloscopes, that it will prove most effective.]

Demonstration

(ii) The inverse of a Fourier analyzer is a Fourier synthesizer - and electronic organs act as such when they build up a complicated oscillation from the fundamental and a few harmonics.

For example:

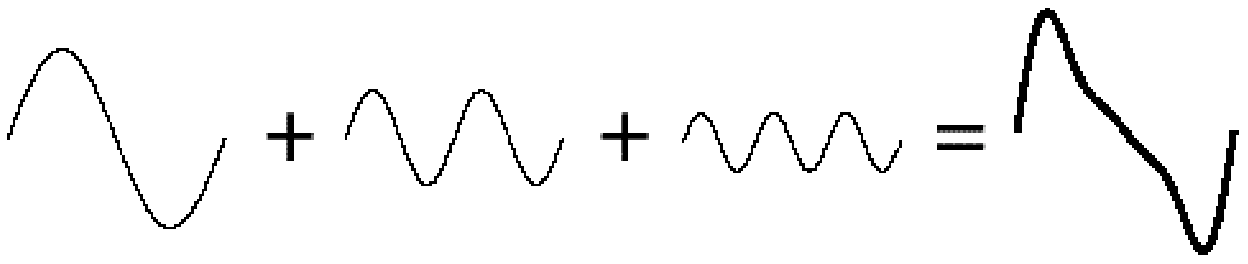

Fig 7.8 Fourier synthesis

If you change only the *phase* of one of these

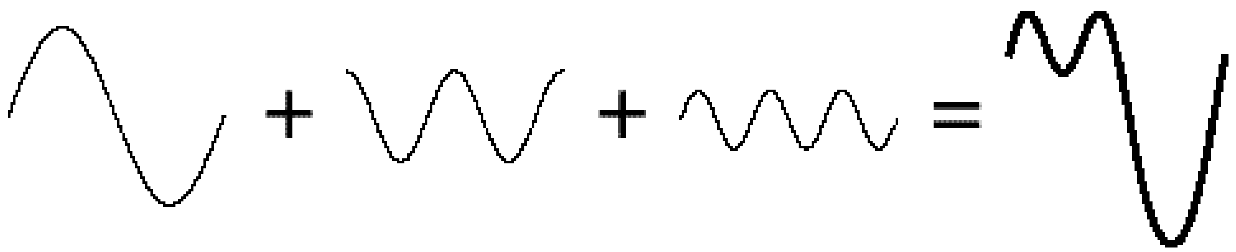

Fig 7.9 Another example of Fourier analysis with a minor change from Fig 7.8

It is a demonstrable fact that the ear cannot distinguish between these two sounds. And though these two pressure-time patterns are quite different, they have the same fourier spectrum - the various harmonics present have the same amplitudes. It is only their phases which are different.

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Demonstration

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POST LECTURE

7-3 REFLECTION AND TRANSMISSION

Actually to calculate how much energy is transmitted or reflected when a sound wave encounters an impedance mismatch, like for example at the ear or a microphone, is very complicated, because it is the mismatch of impedances of the device itself, and the small part of the air right next to it which must be analyzed. However when we consider the passage of a sound wave from one relatively large quantity of one medium to another, things are a little simpler. Then we need to consider only the bulk property of each medium - the specific acoustic impedances.

If a wave of amplitude Ai is incident on a boundary between two media; and a wave of amplitude A_r is reflected from the boundary; then the **sound power reflection coefficient** α_r, defined as the ratio of reflected sound energy to incident flow or sound energy, is given by

$$\alpha_r = \frac{A_r^2}{A_i^2} = \left(\frac{z_2 - z_1}{z_2 + z_1}\right)^2$$

where z_1 and z_2 are the specific acoustic impedances of the media before and after the boundary.

It can be appreciated immediately that complete transmission (i.e. $\alpha_r = 0$) will only occur when the two media have exactly the same specific acoustic impedances.

Q7.1: Why can you hear small sounds so much more clearly under water than in air? [ANS 9]

7-4 IMPEDANCE MATCHING

When there is an impedance mismatch between two media, it is possible to take steps to increase the transfer of energy between the two. One method, for specific devices, was mentioned in the lecture. For large quantities of the media, this can be done by intervening a third medium between the two. Then so long as the specific impedance of this third medium is intermediate between that of the first two, it is found that the transmission of energy is greatly increased.

Perfect transmission of energy occurs, in theory, when

$$z_3 = \sqrt{z_1 z_2}$$

(where z3 is the specific impedance of the intervening medium) and where the thickness of the medium is a quarter wavelength.

You may recall from your optics lecture (L4) that a very similar condition - with refractive index rather than specific acoustic impedance - describes the ideal way to reduce reflections at air to glass boundaries in optical systems.

7-5 FREQUENCY RESPONSE OF THE EAR

Because of physical limitations, the ear will not respond to all frequencies. The main limitation comes from the geometry of the cochlea. If you remember what you have learnt about resonance, then a solid body can resonate with a sound wave if its size is roughly similar to the wavelength of the sound (in that material). Hence if you consider the basilar membrane to look schematically like this

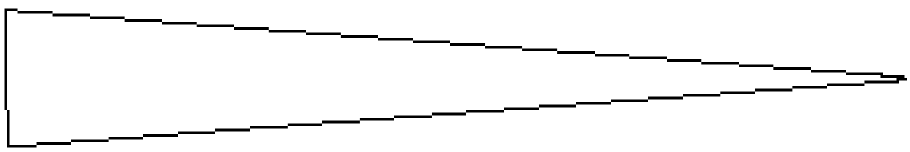

Fig 7.10 A veryschematic representation of the basilar membrane

The lowest frequency it can pick up well will correspond to the width of the big end, and the highest frequency will correspond to the width of where exactly the last nerve cell is located at the small end.

However, there are other factors which limit the frequency range, especially at the high frequency and the most important is the elasticity of the eardrum. This determines its ability to follow a very high frequency vibration. It is found, and you would expect it to be so, that as people age, the elasticity of their skin decreases and so therefore does the highest frequency they can hear. For young people, the upper range is about 20 - 30 kHz, but in middle age, it is found that the upper limit of hearing can drop by 80 Hz every six moths.

Also the state of the joints in the ossicular chain clearly influence frequency response, since these too must vibrate at the same frequency as the drum.

Also the state of the joints in the ossicular chain clearly influence frequency response, since these too must vibrate at the same frequency as the drum.

Q7.2: In general how would you expect that the frequency range of the ear would vary with the **size** of the animals? [Ans 25]

7-6 REFERENCES

Bekesy "The Ear" *Scientific American*, August 1957, p 66.

van Begerjk et al "Waves and the Ear", *Heinemann Science Study Series*.