**Chapter 17: Vibrations and Sound**

***Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier.***

“*If you want to find the secrets of the universe, think in terms of energy, frequency and vibration*.”
Nikola Tesla

**Questions to make you think**

1. Why does sound (usually) travel more quickly in a solid than in a gas?
2. Why does sound (usually) travel more quickly if the temperature is hot?
3. Why does your voice sound different when you hear it played from a recording compared to when you hear yourself speak, and why are we always so uncomfortable when we hear what we sound like to others?

**Student Notes**

We know from the last chapter that sound is a wave motion. We know this because sound undergoes

* Reflection (echoes)
* Diffraction (you can hear around corners)
* Refraction (Explains why sometimes we don’t hear thunder from far away lightning\* )
* Interference (see next demonstration)

**To demonstrate *interference* of sound**

Use a ***signal generator*** and loudspeakers



* Walking slowly from A to B, you will notice the loudness of the sound increasing and decreasing at regular intervals.

This is because sound waves from the two speakers will interfere both constructively and destructively, along the path AB.

NB: You *must* make reference to a signal generator or sound from each speaker having the same frequency.

*{Noise-cancelling headphones are based on the physics of interference: These headphones have a tiny microphone and speaker built in. The microphone detects the external sound and the speaker then generates a sound wave that (in theory) is 180° out of phase with the external sound and cancels it out – this is an example of destructive interference.*

*You can even get these for folk who operate noisy equipment like tractors or jackhammers which cancel out the loud sound but still enable the operator to hear co-worker’s voices!}*

**To show that Sound needs a medium to travel through\***



1. Set up the Bell-Jar – the bell can be heard ringing.
2. Remove the air from the Bell-Jar using a vacuum pump.
3. Result: While the bell can still be seen to be ringing, the sound gets quieter until eventually nothing can be heard\*

Who first discovered this? – the Irishman Robert Boyle (of *Boyle’s law* fame) - that’s who.

**Natural frequency**

**The natural frequency of an object** is the frequency at which the object will vibrate if free to do so.

*{Note that few sounds vibrate at one frequency only – most vibrate at a fundamental frequency plus a combination of overtones* *– see the reference to ‘quality of a note’ at the end of the chapter’.*

**Factors which determine the natural frequency of a stretched string**

* Frequency is inversely proportional to the *length* of the string: f ∝ 1/L
* Frequency is directly proportional to the square root of the *tension* in the string; f ∝ √T
* Frequency is inversely proportional to the square root of the *mass per unit length* of the string; f ∝ 1/√µ.
µ (pronounced “mew”) represents ‘mass per unit length’ and is a bit like saying ‘the density of the string material’)

{But there is a key difference between *density* and *mass per unit length*: take two identical strings (equal densities), then stretch one out; this one now still has the same *density* but has a lower *mass per unit length*.}



Putting these together, and letting the proportional constant = ½ (well why not?) we get:

**Sample question**

A sample of wire was being tested for use as a guitar string. It has a mass per unit length of 0.004 kg m-1.

A 64 cm length of the wire was fixed at both ends and plucked. The fundamental frequency of the sound produced was found to be 173 Hz. Calculate the tension in the wire.

**Solution**

*l* = 64 cm = 0.64 m

*f* = 173 Hz

*µ* = 0.004 kg m-1

T =?

We need to rearrange the equation above to get *T* on its own:





4*l*2*f*2 = $\frac{T}{µ}$  $µ$ 4*l*2*f*2 = *T* *T* = (0.004)(4)(0.64)2(173)2
**Answer:**
T = 196 N

**Resonance\***

**Resonance** is the transfer of energy so that a body vibrates at its natural frequency.

 **To demonstrate resonance**

* Use two ***identical*** tuning forks (same frequency) and a sound-board.
* Start one fork vibrating, place it on the sound-board and notice the sound.
* Place the second tuning fork on the sound-board and then stop the first tuning fork from vibrating.
* The second fork can now be heard.

Explanation:

The vibrations were passed from the first tuning fork via the sound-board to the second tuning fork.
*NB: you must make reference to the fact that both tuning forks are of the same frequency*

**Examples of resonance**:

* Most damage caused to buildings during earthquakes happens because the frequency of the earthquake’s vibrations matches the natural frequency of the walls of the building.
* Resonance is often something that causes problems and mechanical engineers usually need to ensure that the natural frequency of an engine component *does not match* the driving frequency of the engine.

**Frequency limits of audibility**

These are the highest and lowest frequencies that can be heard by a normal human ear.The range is 20 Hz – 20,000 Hz.

*{Frequencies below 20 Hz are known as ‘infrasonic’; elephants and whales communicate in this range, but not necessarily with each other. The other extreme is known as ‘ultrasonic’. This is the frequency that your mom chooses to broadcast at when she finds a wet towel on the bathroom floor. It is not yet known why they do this and for some reasons scientists have been reluctant to ask them directly}*

**Sound intensity**

**Sound intensity** is defined as power per unit area.

$$Sound intensity = \frac{Power}{Area}$$

The unit of sound intensity is therefore the watt per metre squared (W m-2)

Sound energy dissipates equally in all directions (like a spherical balloon being blown up). It follows that the area it is passing through corresponds to the surface area of this sphere: **(formula for the surface areas of a sphere = 4πr2).\***

**Exam question**

A loudspeaker has a power rating of 25 mW.

What is the sound intensity at a distance of 3 m from the loudspeaker?

**Solution**

$Sound Intensity=\frac{25 ×10^{-3} }{4π(3)^{2}}$ S.I. = 2.21 × 10-4 W m-2

**The threshold of hearing\*** is the smallest sound intensity detectable by the average human ear at a frequency of 1000 Hz.
Its value is 1 x 10-12 W m-2

**Sound intensity level and the decibel scale**

Human hearing falls between approximately 10 W m-2 and 1 W m-2.

The former is known *as the threshold of hearing* and the latter is known as *the threshold of feeling*.

The size of this range is enormous and very impractical so instead we use a more compact version of this scale called the *sound intensity level scale*.
The numbers are called ***sound intensity levels*** and are measured in ***decibels* (dB)** so the scale is also sometimes called ***the decibel scale (the dB scale).***

**Examples of sound intensity levels**

|  |  |  |  |
| --- | --- | --- | --- |
| Whisper = 20 dB | iPod at max volume = 100 dB | Threshold of Pain = 130 dB | Perforation of Eardrum = 160 dB |

**Note: doubling the *sound intensity* increases the *sound intensity level* by *3dB***

*This is quite possibly the most useless fact on the whole course (and there was some tough competition for that position) but it has been asked (either directly or indirectly) a few times in exams, e.g. 2007 12 (b), 2011 8(b).*

**Example 1**

The sound intensity doubles as a person approaches a loudspeaker.

What is the increase in the sound intensity *level*?

**Answer**: 3 dB

**Example 2**

The sound intensity level at a concert increases from 85 dB to 91 dB when the concert begins.

By what factor has the sound intensity increased?

**Solution**

Every time that the sound intensity doubles it means that the sound intensity *level* increases by 3 dB, so if intensity has increased by 6 dB then the sound intensity must have doubled, then doubled again.

So the sound intensity level has got 4 times bigger, or has increased by a factor of 4.

**The *decibel adjusted dB(A) scale***

**The decibel adjusted scale is used because it is adapted to the ear’s frequency response\***.
The ear is most sensitive to frequencies between 2000 Hz and 4000 Hz and the decibel adjusted scale takes this into account.The sound-level meter used by environmental engineers has a decibel adjusted scale.

**Speed of sound in different media\***

In general, the speed of sound of sound in a solid is greater than in a liquid, which in turn is greater than that for a gas.

The speed of sound in air (at a temperature of 20 0C) is 343 m s-1.

*{Whales talk to each other by making a loud clicking noise. The sound waves travel extremely well underwater so they can hear each other from 100 miles away.
I know what you’re thinking: this means the poor dads never get a break from either the wife or the kids – torture!*

*On a more serious note, it’s believed that some whale species (eg the blue whale) used to be able to communicate like this over thousands of kilometres but due to noise pollution this is now down to 100 km. It is not known what effect this reduced distance has on the whales. But one imagines it can’t be good. It also seems that some whales are now communicating at frequencies two thirds of an octave higher than they used to; presumably this is also an attempt to overcome artificial background noise.}*

*Prior to World War II and the invention of radar, acoustic mirrors were built as early warning devices around the coasts of Great Britain, with the aim of detecting incoming enemy aircraft by the sound of their engines.*

**Harmonics**
Frequencies which are ***integer*** multiples of the fundamental frequency *f* are called harmonics.
The basic frequency is called the fundamental frequency or first harmonic, 2*f* is the second harmonic etc.

**Overtones**
Frequencies which are multiples of a given frequency are called overtones.
If *f* is the first frequency, then 2*f* is its first overtone; 3*f* is its second overtone etc.

*{It’s not clear from textbooks, but the difference between the two definitions lies in the fact that many membrane-type musical instruments can vibrate at a frequency which is not an integer multiple of the fundamental.
For example, the first overtone of a circular drum is approximately 2.4 times its fundamental resonance frequency.}*

**Harmonics in a pipe open at one end Harmonics in a pipe open at both ends**



**Characteristics of notes**

1. **Loudness**: The loudness of a note depends upon the amplitude of the sound wave\*.
2. **Pitch**: The pitch of a note depends upon the frequency of the sound wave
3. **Quality**: *{Few sounds vibrate at one frequency only – most vibrate at a fundamental frequency plus overtones.}*The quality of a note depends upon the number of overtones present in the note and the relative strengths of those different overtones.\*

This explains why a middle C note sounds different when played on different musical instruments.
*{This occasionally comes up as an exam question}*

**The physics of music**

**Acoustics** **may be defined as the science of sound *{Pythagoras*** *was probably the first person who tried to analyse music mathematically. He discovered that music was pleasing if two strings of the same type and tension have lengths in the simple ratio 2:1, 3:2 or other simple rations – these sound harmonious.*

*More complex ratios are discordant and unpleasant to the ear – and often produce beats which are uncomfortable.}*

**Physics, Musical Scales and Standard Concert Pitch**

Musical scales evolved over the centuries and were different in different parts of the world, both in the number of intervals in the scale and the pitch of the notes.

The Chinese use totally different sets of musical intervals to Europeans.

African music has much smaller intervals, with two or four times as many notes in their scales as in European scales.

Traditionally, European music has developed from a scale of eight notes based on natural ratios of frequencies where the eighth note, the octave, has twice the frequency of the first. This is called the diatonic scale.

Tuning forks found in laboratories are usually in scientific pitch which is not the same as the pitch of corresponding notes on an equally tempered scale and are thus unsuitable for tuning musical instruments.

We must remember that our scales are only conventions adopted for pitch tuning and that singers, trombone and stringed instrument players can easily alter the pitches they produce which may not necessarily match the pitches of standard scales. Generally, the simplest scales are found in old music and the music of non-literate cultures whose creators were not even aware of the theoretical concept of scales, while more complex scales occur in more developed cultures.

**Why do we have the decibel scale?**
The standard answer is that the range of *sound* *intensities* is so large that a second, much more compact scale is required to make the numbers more manageable, and for sound this scale is based on multiples of ten and is called the decibel scale (and what it measures is called *sound intensity level*s).

That’s the official line - I don’t believe a word of it.

The old syllabus included a mathematical description of the decibel scale so the student could actually appreciate the significance of the numbers. When the new syllabus (2002 onwards) was being developed it must have seemed that this mathematical description was too taxing so it was scrapped, except for one very odd 'fact'; *the student must know that a doubling of the sound intensity results in an increase of sound intensity level of  3 dB*. This useless piece of trivia is probably only there as a sop to some university professor who was horrified that the detailed analysis was dropped in the first place. It’s a wonderful example of what happens when you get a committee to design anything.

At least that’s what I used to think, until I read a book on physics and music entitled *How Music Works* by John Powell. This is what he reckons happened:

*“I have no proof of this, but I think the decibel was invented in a bar, late one night, by a committee of drunken electrical engineers who wanted to take revenge on the world for their total lack of dancing partners.”*

You can see immediately see that this idea is much more plausible than mine. I respectfully withdraw my hypothesis.

**Mandatory Experiments:**

* Measurement of the speed of sound in air.
* Investigation of the variation of fundamental frequency of a stretched string with length.
* Investigation of the variation of fundamental frequency of a stretched string with tension.

**That’s all folks!**

**Leaving Cert Physics Syllabus**

|  |  |  |  |
| --- | --- | --- | --- |
| **Content** | **Depth of Treatment** | **Activities** | **STS** |
|  |  |  |  |
| 1. Wave nature of sound | Reflection, refraction, diffraction, interferenceSpeed of sound in various media. | Demonstration of interference, e.g. two loudspeakers and a signal generator.Demonstration that sound requires a medium. | Acoustics.Reduction of noise using destructive interference. Noise pollution. |
|  |  |  |  |
| 2. Characteristics of notes | Amplitude and loudness, frequency and pitch, quality and overtones.Frequency limits of audibility. |  | Dog Whistle |
|  |  |  |  |
| 3. Resonance | Natural frequency. Fundamental frequency.Definition of resonance and examples. | Demonstration using tuning forks *or* other suitable method. | Vocal cords (folds) |
|  |  |  |  |
| 4. Vibrations in strings and pipes | Stationary waves in strings and pipes. Relationship between frequency and length.**Harmonics in strings and pipes.** **for a stretched string.** | Use string and wind instruments, e.g. guitar, tin whistle.**Appropriate calculations.** | String section and woodwind section in orchestras. |
|  |  |  |  |
| 5. Sound intensity level | **Sound intensity: definition and unit.**Threshold of hearing and frequency response of ear. Sound intensity level is measured in decibels.**Doubling the sound intensity increases the sound intensity level by 3 dB.**The dB(A) scale is used because it is adapted for the ear’s frequency response. | Use of sound-level meter. | Examples of sound-level meter.Hearing impairment.Ear protection in industry, etc. |
|  |  |  |  |
| Experiments:1. Measurement of the speed of sound in air.2. Investigation of the variation of fundamental frequency of a stretched string with length.3. Investigation of the variation of fundamental frequency of a stretched string with tension. |

**TO MEASURE THE SPEED OF SOUND IN AIR**

**APPARATUS**

Graduated cylinder, resonance tube open at both ends, tuning forks of known frequency, metre stick, digital callipers

**DIAGRAM**



**PROCEDURE**

1. Set up the apparatus as shown in the diagram
2. Strike one of the tuning forks on a block of wood and hold it over the resonance tube.
3. Move the inner-tube slowly until the first loud resonant sound is heard.
4. Measure the distance from the top of the resonance tube to the top of the water (*l* ). This is approximately one quarter of the wavelength.
5. Measure the inner-diameter of the resonance tube (*d*) using the digital callipers.
6. Note the frequency of the tuning fork; this corresponds to the frequency of the vibrating air column in the resonance tube.
7. The wavelength of sound is calculated using the formula: c = 4f (*l*+0.3*d*)
8. Repeat the procedure with tuning forks of different frequencies. Tabulate the results and get an average value for the speed of sound in air.

**RESULTS**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Frequency(Hz) | Length(m) | c = f (4l)(m/s) | diameter d (m) | 0.3 d(m) | (l+0.3d) | c = 4f(l+0.3d)(m s-1) |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |

Caverage =

**CONCLUSION**

We got an average value for the speed of sound to be 300 m s-1, which compares none too favourably with the theoretical answer of 343 m s-1. But given that the answer is temperature dependent, it may well be the case that we did our experiment perfectly, but just happened to be a corner of the lab which was at -50 0C.

**PRECAUTIONS**

1. Ensure that your eye is level with the top of the tube when measuring the length to avoid parallax error.
2. Start with the inner tube fully in the water and slowly raise it so that you don’t get a harmonic by mistake.
3. Repeat your efforts to find the loudest resonance position for each tuning fork. Take the average of the attempts.

**So where does the formula *c = 4f(l+0.3d*) come from?**

From our notes we know that for a standing wave the length from node to anti-node is one quarter of the wavelength.

⇒ Length from node to anti-node is = λ/4



Now it’s not at all obvious from this diagram that the wave shape is merely a mathematical representation of the relative size of the disturbance of the air molecules, but that’s what it is. On the left hand side (the node) there is almost no disturbance, while on the right hand side (the anti-node) there is maximum disturbance.

Now this is all fine in theory, but in practice we have a 3-dimensional tube, and it turns out that the maximum displacement of the air molecules is not just at the top of the pipe, but a little outside it. This extra distance is approximately 0.3 times the diameter. Exactly why it’s 0.3 is beyond the scope of this discussion (which is another way of saying I have no idea). I guess it just is. At any rate that would be the engineering response.

In Physics we try to go for the underlying explanation; Engineers really just don’t care. That is why physicists have nothing but contempt for engineers and everything they stand for. So it doesn’t really seem fair that for every student of mine who goes on to study Physics in college, ten go on to do Engineering - a fact which continues to haunt me every day of my life.

But I digress . . .



In this case that means

(Length of tube plus correction term) = λ/4

⇒ λ = 4 (Length of tube plus correction term)

⇒ λ = 4 (l + 0.3d)

Now we know c = fλ

⇒ c = f [**4 (l + 0.3d)]**

⇒ c = 4f (l + 0.3d)

That you should have to remember this formula is nothing short of ridiculous. In no way does it enhance your understanding of the concepts involved. Not only that, but there a number of other ways to do this experiment that never need to use this formula and the syllabus specifically says that any method will do for exam purposes. But then in 2006 (Question 3) they asked a question that related specifically to this method, even going to far as to give the diameter of the tube, so you had to know this formula. Not very nice.

**Important lesson on how to be a good scientist: *CHEAT !!!***

We can ignore the small correction term in order to give us a rough idea of what L should be:

c = f λ ⇒ c = f (4L ) ⇒ 340 = 4(f)(L) ⇒ L = 340 / 4 (f)

Now check this each time before you put a value for L into your table.

(Technically we refer to this as ‘checking in advance’; a carpenter would use the phrase “measure twice, cut once”).

**INVESTIGATION OF THE VARIATION OF FUNDAMENTAL FREQUENCY OF A STRETCHED STRING WITH LENGTH**

**APPARATUS:** Sonometer, newton-meter, tension key, signal generator, u-magnet

**DIAGRAM**



**PROCEDURE**

1. Set up as shown on the diagram.
2. Fix the tension at a constant value.
3. Place the bridges as far apart as possible and measure the length of the wire l between the bridges with a metre stick.
4. Slowly increase the applied a.c. frequency from 0 Hz until the paper-rider vibrates the most.
5. Note the value of this (fundamental frequency) and the length of the wire.
6. Repeat this procedure for different lengths of wire by varying the distance between the bridges.
7. Record the measurements in a table.
8. Plot a graph of frequency f against 1/length.

**RESULTS**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| f (Hz) |  |  |  |  |  |  |  |  |
| l (m) |  |  |  |  |  |  |  |  |
| 1/l (m-1) |  |  |  |  |  |  |  |  |

**CONCLUSION**

We obtained a straight line through the origin which verifies that frequency is inversely proportional to the length.

**PRECAUTIONS / SOURCES OF ERROR**

1. Determining exactly where the resonance point is can be tricky so for each length repeat a few times and get an average.
2. Avoid parallax errors when using a metre stick to measure the length of the wire.

**NOTES**

1. **The** **Signal** **Generator**

Instead of using the signal-generator and U-magnet, you could just use a tuning fork to generate a vibration of a set frequency (set it vibrating and then stand it either on the sonometer or on one of the bridges). You then vary the position of the second bridge until you reach resonance. In theory this is simpler; in practice it is much more difficult to detect the resonance position because the string doesn’t vibrate sufficiently.

You may find the Signal Generator cutting out quite often if you have the current (Ampllitude setting) up quite high, so if you need a high current just use at that setting for as briefly as possible).

If you do go with the signal generator in the exam, you *must* remember to include the magnet also.

Exactly why this method works is conveniently ignored for now. But we do go into the theory in Chapter 27: Current in a Magnetic Field.

1. **The** **paper** **rider**

If a paper rider is used to locate resonance, place it mid-way between the bridges.

Keep the paper rider as light as possible. Use a small piece of cellotape to hold the paper in the form of a loop.

A short length of drinking straw can also be used as a very light rider. This rider can be moved along the string to detect the positions of nodes and antinodes when the string is vibrating at resonance.

1. Instead of using a newton-metre and a tension-control key you could use weights which hang off of one end.
2. Wear safety goggles in case the sonometer wire snaps and you lose an eye. Because as everybody knows, it’s all fun and games until someone loses an eye. Then the tears will start . . .

**INVESTIGATION OF THE VARIATION OF FUNDAMENTAL FREQUENCY OF A STRETCHED STRING WITH TENSION**

**APPARATUS**

Sonometer, newton-meter, tension key, signal generator, u-magnet

**DIAGRAM**



**PROCEDURE**

1. Set up as shown on the diagram.
2. Fix the length at a constant value.
3. Set the tension to a low value.
4. Slowly increase the applied a.c. frequency from 0 Hz until the paper-rider vibrates the most.
5. Note the value of this frequency and the tension on the wire.
6. Repeat this procedure for different tensions by varying the tension-control key.
7. Record the measurements in a table.
8. Plot a graph of frequency f against the square root of tension.

**RESULTS**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| f (Hz) |  |  |  |  |  |  |  |
| T (N) |  |  |  |  |  |  |  |
| √T (N1/2) |  |  |  |  |  |  |  |

**CONCLUSION**

A straight line through the origin will verify that frequency is proportional to the square root of tension.

**PRECAUTIONS / SOURCES OF ERROR**

Determining exactly where the resonance point is can be tricky so for each tension repeat a few times and get an average.

**Extra Credit**

**\*Refraction (Explains why sometimes we don’t hear thunder from far away lightning)**

Different layers of air are at different temperatures, and sound travels at different speeds in the different layers (quicker in warmer air which is closer to the ground), as a result the sound wave bends away from the ground).

**\*Sound needs a medium to travel through**Astronauts cannot speak to each other on the moon without the aid of radio waves because of the lack of air.In one film, when the microphones broke down, the two astronauts put their helmets together, thus transmitting the sound vibrations through the helmets. Sometimes, in popular science fiction films, we see and hear an explosion in space which is incorrect as the sound waves, unlike light, cannot travel through empty space.

**\*While the bell can still be seen to be ringing, the sound gets quieter until eventually nothing can be heard.**
In practice a little sound can still be heard – why?
Partly because it isn’t a complete vacuum and partly because the electrical leads conduct some sound to the outside.

Actually the main reason that the sound decreases in this demo is not because sound can’t travel in a vacuum (although this is indeed true), but rather due to a very different concept called *Impedance Mismatch*.

**\*Resonance – What a wonderful concept!**
Resonance is one of my favourite topics in Physics.
It explains such a wide range of different phenomena, from a swing pushed at its natural frequency to offering a possible explanation for the collapse of the Walls of Jericho, to tuning in radios.

**Tacoma Narrows Bridge Collapse**

Washington ; The wind produced an oscillating resultant force in resonance with a frequency equal to a natural frequency of the bridge, causing it to vibrate with such large amplitude oscillations that it completely collapsed.

Cooling towers and factory chimneys can also be set oscillating by the wind at their natural frequencies.

**Vibrations in Washing Machines**
Washing machines may vibrate violently at particular speeds because resonance occurs when the frequency of the rotating drum equals a natural frequency of the body of the machine. There are usually several natural frequencies at which resonance can occur. Some machines have a block of concrete attached to the outer drum and the consequent increase in mass reduces the amplitude of any vibrations that might build up during washing or spinning.

**Rattling Windows**

Passing vehicles producing vibrations matching the natural frequency of a window in a nearby building can cause the windows to resonate.

**The ‘brown’ note**Unfortunately this is a bit of an urban myth; it’s the idea that sound at about 5 to 10 Hz will ‘stimulate’ your bowels and induce ‘a movement’.Apparently it can happen if you are strapped to a seat which is set vibrating (they tested this with astronauts because they were worried about what might happen at lift-off where changing facilities would be rather limited). But air, in contrast, is poor at transferring low-frequency vibration as sound.

**NicolaTesla and resonance**

…With George Scherff present, Tesla placed one of his mechanical oscillators on the centre support beam in the basement of the Heuston Street building where his laboratory was located and adjusted the frequency to the point where the beam began to hum. “While he was attending to something else for a few moments, it attained such a crescendo of rhythm that it started to shake the building, then it began shaking the earth nearabout [and other buildings with support beams in resonant frequencies] … The fire department responded to an alarm frantically turned in; four tons of machinery flew across the basement and the only thing which saved the building from utter collapse was the quick action of Dr. Tesla in seizing a hammer and destroying his machine.”

“The device could be a Frankenstein’s monster,” Tesla confided many years later. “If not watched, no substance can withstand the steadily applied rhythm when its resonant point is reached. Skyscrapers could easily be destroyed with the steady building up of resonance from the timed strokes of a five-pound hammer.”

In another rendition to the story, told at another time, Tesla claimed that he had taken his alarm clock-sized oscillator to a building site “in the Wall Street district.” Finding one under construction, about “ten stories high of steel framework …” he clamped the vibrator to one of the beams and fussed with the adjustment until he got it.

“In a few minutes I could feel the beam trembling,” Tesla told a reporter. “Gradually, the trembling increased in intensity and extended throughout the whole great mass of steel. Finally, the structure began to creak and weave, and the steelworkers came to the ground panic stricken, believing that there had been an earthquake. Rumours spread that the building was about to fall, and the police reserves were called out. Before anything serious happened, I took off the vibrator, put it in my pocket and went away. But if I had kept it on ten minutes more, I could have laid that building flat in the street. And, with the same vibrator, I could drop the Brooklyn Bridge into the East River in less than an hour.”Tesla told the reporter that he could split the Earth in the same way, putting and end to mankind.

“The vibrations of the Earth,” he said, “have a periodicity of approximately one hour and forty-nine minutes. That is to say, if I strike the earth this instant, a wave for contraction goes through it that will come back in one hour and forty-nine minutes in the form of expansion. As a matter of fact, the Earth, like everything else, is in a constant state of vibration. It is constantly contracting and expanding.

 Now suppose that at the precise moment when it begins to contract, I explode a ton of dynamite. That accelerates the contraction, and in one four and forty-nine minutes, there comes an accelerated wave of expansion. When the wave of expansion ebbs, suppose I explode another ton … and suppose this performance be repeated time after time. Is there any doubt as to what would happen? There is no doubt in my mind. The Earth would be split in two. For the first time in man’s history, he has the knowledge with which he may interfere with cosmic processes.”

Tesla calculated that this procedure might take more than a year to succeed, “but in a few weeks,” Tesla said, “I could set the Earth’s crust into such a state of vibration that it would rise and fall hundreds of feet, throwing rivers out of their beds, wrecking buildings, and practically destroying civilisation. The principle cannot fail.”

Taken from *Wizard; A biography of Nikola Tesla* (pps 190, 191)
See also ‘The man who invented the twentieth century, available from the physics library.

Tesla was indeed one of the most important scientists of the 20th century, but one who has been mostly forgotten.
He now has what could be described as a ‘cult following’ on the internet.

Apparently *Mythbusters* tried this and found that while they weren’t able to collapse a building, there was actually a noticeable effect!!

**Sound Intensity = Power/4πr2**

If you have a light source at the centre of a sphere of surface area 100 sq meters. And each sq meter had a house. All houses get the same sound intensity.

Now if you double the radius of the sphere (go twice as far from the light), then the surface area becomes 400 sq meters. Which accommodates 4 times as many houses as before. So each house receives a 1/4 of what it received
before. This is how an inverse square relationship works; double the distance and the power goes down by four, triple the distance and the power goes down by 9 etc.

**\*… at a frequency of 1,000 Hz*.***

**Why do we have to specify a frequency?**Because just like we are more receptive to some electromagnetic frequencies than others, we are also more receptive to some sound frequencies. The human ear is very sensitive at the 1,000 Hz point.

See also the note on the decibel adjusted scale.

**\*The decibel adjusted scale dB(A) is used because it is adapted to the ear’s frequency response.**A sound gets louder if the sound intensity increases.

However it can get a lot more complicated; if the *frequency* were adjusted while the sound intensity remained constant, we would also think that the sound had gotten louder (or quieter), even though a machine would detect no increase in loudness.

This is because we are more sensitive to some frequencies than others.

So instead of just measuring decibels, we must also bear in mind the frequency involved; the units used to indicate this new quantity are *decibel adjusted (dBA).*

A baby’s cry contains frequencies corresponding to the most sensitive part of the human ear’s frequency range (we are most sensitive to sounds between 2000 Hz and 4000Hz)This means that sounds at these frequencies *seem* louder than sounds at other frequencies. This is because the natural frequency of the main bone in the ear is about 3kHz.

**\*The speed of sound of sound in a solid is greater than in a liquid, which in turn is greater than that for a** **gas**

Remember the Cowboys in the Westerns listening for the sound of an on-coming train by putting their ear to the rail-track?

**\*The loudness of a note depends upon the amplitude of the sound wave**Loudness also depends upon the sensitivity of the listener; we are more sensitive to some frequencies than others – see the dBA.

**\*Quality**

The quality of a note depends upon the number of overtones present in the note

It also depends upon the relative strengths of the different overtones present.

In practice, when a musical instrument emits a given note (corresponding to a certain frequency), it will also emit a number of overtones, but at lower strengths.

Different instruments emit different combinations of overtones, and at different strengths.

**Exam questions**

1. [2006 OL]
2. The speed of sound depends on the medium through which the sound is travelling.

Explain how sound travels through a medium.

1. Why is the speed of sound greater in water than in air?
2. [2006 OL][2008 OL]

Describe an experiment to demonstrate that sound requires a medium to travel.



1. [2008 OL]

The diagram shows a signal generator connected to two loudspeakers emitting the same note.

A person walks slowly along the line AB.

1. What will the person notice?
2. Why does this effect occur?
3. What does this tell us about sound?
4. [2005 OL]
5. In an experiment, a signal generator was connected to two loudspeakers, as shown in the diagram. Both speakers are emitting a note of the same frequency and same amplitude.

A person walks along the line XY.

Describe what the person hears.

1. What does this experiment demonstrate about the nature of sound?
2. [2005][2003]

Describe an experiment to show that sound is a wave motion.

1. [2004 OL]

Describe an experiment to demonstrate the interference of sound.

1. [2007 OL][2010 OL]

Explain the term *natural frequency*.

1. [2007 OL][2010]

Explain the term *resonance*.

1. [2007 OL][2010][2010 OL]

Describe an experiment to demonstrate resonance.

1. [2010 OL]

An opera singer, singing a high pitched note, can shatter a glass. Explain why.

1. [2008]

What is the relationship between the frequency of a vibrating stretched string and its length?

1. [2006]

What is the relationship between frequency and tension for a stretched string?

1. [2005][2004 OL]

The frequency of a stretched string depends on its length.

Give two other factors that affect the frequency of a stretched string.

1. [2009 OL][2007 OL][2010][2010 OL]

Name the property on which the pitch of a musical note depends.

1. [2007 OL][2010][2010 OL]

State the wave property on which the loudness of a note depends.

1. [2010]

State the physical property on which the quality of a note depends.

1. [2010]

Explain why a musical tune does not sound the same when played on different instruments.

1. [2010]

A mobile phone converts the received radio frequency waves to sound waves.

What are the audible frequency limits for sound waves?

**Sound intensity and Sound Intensity Level**

1. [2007][2002]

Define sound intensity.

1. [2004]

The sound intensity doubles as a person approaches a loudspeaker.

What is the increase in the sound intensity level?

1. [2009]

The sound intensity level at a concert increases from 85 dB to 94 dB when the concert begins.

By what factor has the sound intensity increased?

1. [2007]
2. A loudspeaker has a power rating of 25 mW.

What is the sound intensity at a distance of 3 m from the loudspeaker?

1. The loudspeaker is replaced by a speaker with a power rating of 50 mW.

What is the change in the sound intensity?

1. What is the change in the sound intensity level?
2. [2002 OL][2008 OL]

What physical quantity is measured in decibels?

1. [2003]

Sound intensity level can be measured in dB or dB(A).

What is the difference between the two scales?

1. [2007]

The human ear is more sensitive to certain frequencies of sound.

How is this taken into account when measuring sound intensity levels?

**Mandatory Experiments**

**To measure the speed of sound in air**

1. [2008 OL]

You carried out an experiment to find the speed of sound in air, in which you measured the frequency and the wavelength of a sound wave.

1. With the aid of a diagram describe the adjustments you carried out during the experiment.
2. How did you find the frequency of the sound wave?
3. How did you measure the wavelength of the sound wave?
4. How did you calculate the speed of sound in air?
5. Give one precaution you took to get an accurate result.
6. [2003 OL]

 In an experiment to measure the speed of sound in air, a student found the frequency and the wavelength of a sound wave.

1. Draw a labelled diagram of the apparatus used in the experiment.
2. Describe how the student found the wavelength of the sound wave.
3. How did the student find the frequency of the sound wave?
4. How did the student calculate the speed of sound in air?
5. Give one precaution that the student took to get an accurate result.
6. [2006]

A cylindrical column of air closed at one end and three different tuning forks were used in an experiment to measure the speed of sound in air. A tuning fork of frequency f was set vibrating and held over the column of air.

The length of the column of air was adjusted until it was vibrating at its first harmonic and its length l was then measured. This procedure was repeated for each tuning fork.

|  |  |  |  |
| --- | --- | --- | --- |
| f/Hz | 512 | 480 | 426 |
| *l*/cm | 16.0 | 17.2 | 19.4 |

Finally, the diameter of the column of air was measured.

The following data was recorded.

Diameter of column of air = 2.05 cm.

1. Describe how the length of the column of air was adjusted.
2. Describe how the frequency of the column of air was measured.
3. Describe how the diameter of the column of air was measured.
4. How was it known that the air column was vibrating at its first harmonic?
5. Using all of the data, calculate the speed of sound in air.

**To investigate how the fundamental frequency of a stretched string varied with its length**

1. [2006 OL]

A student carried out an experiment to investigate how the fundamental frequency of a stretched string varied with its length. The following is an extract from her report.

I set the string vibrating and adjusted its length until it was vibrating at its fundamental frequency. I then recorded the length of the vibrating string and its fundamental frequency. I repeated this procedure for different lengths of the stretched string.

Finally, I plotted a graph of the fundamental frequency of the vibrating string against the inverse of its length.

1. Draw a labelled diagram of the apparatus used in the experiment.

Indicate on your diagram the length of the string that was measured.

1. Describe how the student set the string vibrating.
2. How did the student know that the string was vibrating at its fundamental frequency?
3. Draw a sketch of the graph expected in this experiment.
4. [2002 OL)

In a report of an experiment to investigate the variation of fundamental frequency of a stretched string with length, a student wrote the following.

“The wire was set vibrating at a known frequency. The length of the wire was adjusted until it vibrated at its fundamental frequency. The length was recorded. A different frequency was applied to the wire and new measurements were taken. This procedure was repeated a few times.”

1. How was the wire set vibrating?
2. How was the length adjusted?

The table shows the measurements recorded by the student.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Fundamental frequency (Hz) | 650 | 395 | 290 | 260 | 192 | 174 | 163 |
| length/ (m) | 0.20 | 0.33 | 0.45 | 0.50 | 0.66 | 0.75 | 0.80 |
| 1/length (m-1) |  |  |  |  |  |  |  |

1. Copy the table and complete the last row by calculating 1/ length1for each measurement.
2. Plot a graph on graph paper of fundamental frequency against 1/ length. Put fundamental frequency on the vertical axis.
3. What does the graph tell you about the relationship between fundamental frequency and length?
4. [2009 OL]

In an experiment, a student investigated the variation of the fundamental frequency f of a stretched string with its length l. During the experiment the student kept the tension in the string constant. The table shows the data recorded by the student.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| f/Hz | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
| l/m | 0.50 | 0.33 | 0.25 | 0.20 | 0.166 | 0.142 | 0.125 |
| 1/l (m− 1) |  |  |  |  |  | 7.04 |  |

1. Describe, with the aid of a diagram, how the student obtained the data.
2. Why was the tension in the string kept constant during the experiment?
3. Copy this table and fill in the last row by calculating 1/l for each measurement.
4. Plot a graph on graph paper to show the relationship between the fundamental frequency and the length of the stretched string (put 1/l on the X-axis).
5. What does your graph tell you about the relationship between the fundamental frequency of a stretched string and its length?

**To investigate the variation of the fundamental frequency *f* of a stretched string with its tension *T***

1. [2009]

A student investigated the variation of the fundamental frequency *f* of a stretched string with its tension *T.*

The following is an extract of the student’s account of the experiment.

“I fixed the length of the string at 40 cm. I set a tuning fork of frequency 256 Hz vibrating and placed it by the string.

I adjusted the tension of the string until resonance occurred. I recorded the tension in the string. I repeated the experiment using different tuning forks.”

1. How was the tension measured?
2. How did the student know that resonance occurred?

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *f* /Hz | 256 | 288 | 320 | 341 | 384 | 480 | 512 |
| *T* /N | 2.4 | 3.3 | 3.9 | 4.3 | 5.7 | 8.5 | 9.8 |

The following data were recorded.

1. Draw a suitable graph to show the relationship between the fundamental frequency of a stretched string and its tension.
2. State this relationship and explain how your graph verifies it.
3. Use your graph to estimate the fundamental frequency of the string when its tension is 11 N
4. Use your graph to calculate the mass per unit length of the string.
5. [2002]

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| T/N | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
| f /Hz | 264 | 304 | 342 | 371 | 402 | 431 | 456 |

A student obtained the following data during an investigation of the variation of the fundamental frequency f of a stretched string with its tension T.

The length of the string was kept constant.

1. Describe, with the aid of a diagram, how the student obtained the data.
2. Why was the length of the string kept constant during the investigation?
3. Plot a suitable graph on graph paper to show the relationship between fundamental frequency and tension for the stretched string.
4. From your graph, estimate the tension in the string when its fundamental frequency is 380 Hz.
5. [2004]

A student investigated the variation of the fundamental frequency *f* of a stretched string with its length *l*.

1. Draw a labelled diagram of the apparatus used in this experiment. Indicate on the diagram the points between which the length of the wire was measured.

The student drew a graph, as shown, using the data recorded in the experiment, to illustrate the relationship between the fundamental frequency of the string and its length.

1. State this relationship and explain how the graph verifies it.
2. The student then investigated the variation of the fundamental frequency *f* of the stretched string with its tension *T*. The length was kept constant throughout this investigation.

How was the tension measured?

1. What relationship did the student discover?
2. Why was it necessary to keep the length constant?
3. How did the student know that the string was vibrating at its fundamental frequency?

**Exam solutions**

1. The molecules vibrate and as a result the energy is then passed from particle to particle.
2. Because the molecules of water are closer together than are the molecules of air, so the energy can be transferred more quickly.
3. 
* Set up the Bell-Jar – the bell can be heard ringing.
* Remove the air from the Bell-Jar using a vacuum pump.
* Result: While the bell can still be seen to be ringing, the sound gets quieter until eventually nothing can be heard.
1. The loudness of the sound increases and decreases at regular intervals.
2. ****Because of interference caused from waves coming from the two speakers.
3. Sound is a wave.
4. The loudness of the sound increases and decreases at regular intervals.
5. It demonstrates that sound is a wave.
6. 
* Set up as shown
* Walking slowly from X to Y, you will notice the loudness of the sound increasing and decreasing at regular intervals.
* This is because sound waves from the two speakers will interfere both constructively and destructively, along the path XY.
1. Same answer as previous question.
2. Natural frequency is the frequency at which an object will vibrate if free to do so.
3. Resonance is the transfer of energy so that a body vibrates at its natural frequency.
4. Use two *identical* tuning forks and a sound-board.
* Start one fork vibrating, place it on the sound-board and notice the sound.
* Place the second tuning fork on the sound-board and then stop the first tuning fork from vibrating.
* The second fork can now be heard.
1. Energy is transferred due to resonance because the singer is singing at the natural frequency of the glass.
2. Frequency is proportional 1/ length
3. Frequency is proportional to the square root of tension.
4. Tension and mass per unit length of the string
5. Frequency
6. Loudness depends on amplitude
7. Quality/timbre: harmonics / overtones
8. Different instruments emit (a fundamental frequency plus) different (combinations of)overtones/harmonics.
9. 20 Hz to 20 000 Hz
10. Sound Intensity is defined as power per unit area.
11. 3 dB
12. If sound intensity doubles ⇒ intensity level increases by 3 dB, so if intensity has increased by 9 dB then the sound intensity must have increased by a factor of 8.
13. Surface area of sphere = 4π *r*2

S.I at 3 m = (25 × 10-3 ) ÷ 4 π (3)2
S.I = 2.21 × 10-4 W m-2

1. Increased by: 2.21 × 10-4 W m-2
2. Increased by: 0.30 B or 3 dB
3. Sound intensity level
4. The dB(A) is adjusted so that it is suitable for the human ear.
5. By using a sound level meter which is most sensitive to sounds between 2kHz and 4 kHz / just like the ear /dBA / decibel adapted / a frequency weighted scale is used
6. 
7. We adjusted the length of the inner tube until resonance occurred.
8. We read it from the tuning fork which was used to create the sound wave.
9. We measured the diameter of the inner tube using digital callipers.

We measured the length of the inner tube above the water.

We then used the formula λ = 4(l + 0.3d) to calculate the wavelength.

1. We substituted the values for frequency and wavelength into the formula c = f λ
2. Repeat using different tuning forks and take an average, clamp tube to take measurements.
3. 
4. See diagram.
5. We measured the diameter of the inner tube using digital callipers.

We measured the length of the inner tube above the water.

We then used the formula λ = 4(l + 0.3d) to calculate the wavelength.

1. We read it from the tuning fork which was used to create the sound wave.
2. We substituted the values for frequency and wavelength into the formula c = f λ
3. Repeat using different tuning forks and take an average, clamp tube to take measurements.
4. The inner pipe was raised while immersed in water.
5. The frequency was read from the tuning fork which caused the vibration.
6. Using a digital calipers
7. The inner tube was raised until a loud sound could be heard.
8. v = f λ

λ = 4( l +0.3 d)

v1 = 340(.3) m s-1; v2 = 342(.0) m s-1 ; v3 = 341(.1) m s-1
vavg = 341(.13) m s-1

1. See diagram.
2. By turning on the signal generator.
3. The paper rider starts to vibrate vigorously.
4. See diagram**.**
5. Using a signal generator in series with a metal wire which had a magnet around it.
6. By moving the position of one of the bridges.

The table shows the measurements recorded by the student.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 1/length (m-1) | 5.0 | 3.0 | 2.2 | 2.0 | 1.5 | 1.3 | 1.25 |

****

1. See graph
2. The straight line through the origin shows that frequency is inversely proportional to length.
3. See diagram

Adjust frequency until the paper rider falls off (resonance occurs)

Record the frequency on the signal generator and measure the length between the bridges.

Adjust the distance between the bridges and repeat.

1. Because frequency also depends on tension and you can only investigate the relationship between two variables at a time.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| f/Hz | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
| l/m | 0.50 | 0.33 | 0.25 | 0.20 | 0.166 | 0.142 | 0.125 |
| 1/l (m− 1) | **2.00** | **3.03** | **4.00**  | **5.00** | **6.02** | 7.04 | **8.00** |

1. 
2. Fundamental frequency is inversely proportional to length
3. A newton balance // weight of pan + contents
4. Paper rider jumped vigorously / the string vibrated at maximum amplitude
* Six correct values for √T
* Both axes correctly labelled
* Six points correctly plotted
* Straight line with a good fit
1. f is proportional to square root of T because the graph was a straight line through the origin.
2. If tension is 11 N ⇒ √T = 3.32

Use the graph to get f = 542 Hz

1. Compare the formula on the right to the formula y = mx ⇒ slope = 1/(2l√μ), where l = 0.4 m

Mass per unit length (μ) = 5.86 × 10–5 kg m–1

1. Slowly increase the frequency on the signal generator until resonance occurs.

Note the frequency on the signal generator and the tension on the Newton balance.

Change tension and repeat.

1. Because length is a third variable and you can only investigate the relationship between two variables at a time.
2. Square root of tension / frequency squared

Label axes

Plot 6 points correctly

Straight line

Good fit

1. At a frequency of 380 the square root of tension= 5.6  T = 30.3 N
2. See diagram
3. f is proportional to 1/l.

A straight line through the origin verifies this.

1. Using a newton-balance / pan with weights / suspended weights
2. Frequency is proportional to √Tension.
3. Because length is a third variable and you can only investigate the relationship between two variables at a time.
4. The paper rider on the string falls off.