SOUND and

Before attempting to discuss at length the subject of high fidelity sound reproduction, it may be helpful to set out some basic facts about the nature of sound itself, the means by which we hear it and factors which determine whether or not we find the experience to our liking. So let's start right there.

Without resorting to the formality of a dictionary, sound may be defined broadly as anything that can be heard, whether it be in the form of noise, speech, music, or whatever.

Not everyone can hear every sound in a given environment because some sounds are so soft that, for certain people, they lie below their so-called "threshold of hearing". Again, other sounds may be too high-pitched for some people's ears to sense.

In the normal way, sound is created when a vibrating mechanical body or other such disturbance produces a sequence of rapidly recurrent variations in air pressure in its immediate vicinity. The variations radiate outwards from the source, through the surrounding air in the form of sound pressure waves, much like ripples in a pond.

On reaching a person's ears, the recurrent pressure waves are sensed by means we shall examine a little later. Transformed into neural (nerve) impluses, they then pass to the brain, where they are interpreted as "information" of one kind or another: noise, speech, &c.

Fig.1 illustrates the simplest, purest tone that can be presented to the human ear — a "sine" wave, so called because it has a mathematical basis. Sine waves, or something very similar to them, are produced by electronic organs and music synthesisers and are employed in audio test equipment.

Some traditional music sounds, and the associated air pressure variations, are relatively simple, for example, single notes from a solo flute; others are extremely complex, like those from an orchestra, a concert organ or a large choir.

The amazing thing is that, simple or complex, the human brain is able to sort out pressure variations sensed by the ear and translate them into something we can relate to or, alternatively, ignore!

How many times have you been absorbed in a book and apparently not heard sound that must clearly have reached your ears? Or conversely, been asleep and ostensibly unaware of any sound — except one that your "sleeping brain" considered important enough to let through?

Sound pressure level

Sound pressure level (SPL) can be expressed in microbars, reminiscent of the millibars used to specify atmospheric pressure in weather reports. In the context of audio-hifi, however, sound pressure level is commonly expressed nowadays in dynes/sq.cm, a unit that is quantitatively equivalent to the microbar.

The smallest sound pressure level that can be sensed by young, healthy human ears — the so-called threshold of human hearing — is about 0.0002 microbar. By comparison, a person talking generates a sound pressure level of around 1 to 2 microbars, at a distance of 1 metre, and up to 10 microbars when shouting.

Typical human ears can cope with sound pressure levels up to about 200 microbars without obvious aural overload. At pressures approaching and beyond 2000 microbars, however, sounds become physically painful and may damage the hearing with prolonged exposure.

Many old-time boilermarkers learned this the hard way!

Meet the decibel

While the foregoing figures are informative, they are also rather clumsy and they take no account of one very important fact: that the ear varies its sensitivity automatically as the prevailing level of sound rises or falls. It transpires that the loudness of sound, as perceived, varies approximately as the logarithm of the change in acoustic power level.

It is because of this characteristic that the ear can cope with such an enormous range of sound pressure levels — from the barely audible hum of a mosquito in a quiet room to the massive roar of a jetplane at take-off.

WAVES... how we hear them

by NEVILLE WILLIAMS

The "decibel", a logarithmically based unit, was adopted many years ago by the audio-acoustics industry, as a more eloquent way to express relative power levels, especially as they affect people needing to quantify original or reproduced sound on an everyday basis.

A power ratio can be converted to decibles (dB) by determining the log (to the base 10) of the particular ratio, multiplying it by 10 and calling the result decibels (dB).

Since the acoustic power of a sound varies as the square of the sound pressure level, the log of the pressure ratio has to be multiplied by 20, rather than by 10. A pressure ratio of 10:1 works out at 20dB, 100:1 at 40dB, 1000:1 at 60dB and so on.

Research has shown that the smallest change in sound pressure level (SPL) that human ears can easily detect is about 3dB, equal to a power ratio of 2:1. It may come as a surprise to realise that doubling the acoustic power of a sound, or the available power output from an amplifier, makes only a marginal difference to the perceived loudness!

Decibel notation was subsequently adapted by the industry to express absolute sound pressure levels, as distinct from mere ratios, by arbitrarily referencing 0dB to the nominal threshold of hearing at 0.0002 microbar.

This provides the basis for Table 1, and many others like it, showing 0dB as the threshold of hearing, 40dB as the ambient sound level in a typical living room, 60dB as an average conversational level and 140dB as the pain threshold.

Amplitude, frequency

The magnitude of the upward/downward excursions in instantaneous pressure is referred to as the "amplitude" of a sound wave — miniscule for tiny sounds, just the reverse for jet planes. Fig.1b depicts the peak-to-peak amplitude of a sound pressure wave, and the RMS value on which the acoustic power is based.

(Amplitude is a term that is encountered frequently in audio/hifi literature, being used to describe the magnitude of signals passing through an audio amplifer, the physical movement of loudspeaker cones and so on.)

Sound waves travel through normal atmosphere at about 335 metres (1100ft) per second, much slower than radio waves (or light waves) at around 300,000km/s.

For a sine wave or a simple tone propagating through air, a complete pressure excursion from normal to maximum, then through to minimum and back to normal is referred to as one "cycle" (Fig.1b).

The number of complete cycles passing a given point in space in one second is described as the "frequency" of the signal.

Audio frequencies were originally specified in cycles per second (c/s) or kilocycles per second (kc/s). In honour of the pioneer German physicist, Heinrich Hertz (1857-1894) c/s was subsequently replaced by the term "Hertz" (Hz) along with its decimal multipliers, kHz, MHz, &c.

The distance between adjacent pressure peaks is defined as the "wavelength" (Fig.1a). Without dwelling on the matter here, the wavelength of sound energy has an important bearing on its behaviour in a domestic hifi situation, especially in regard to loudspeakers and listening room dimensions.

Sense of hearing

So much for the nature of sound. Before pursuing it further into the everyday world of music, speech and noise, let's take a closer look at human hearing — undoubtedly a most discriminating faculty.

At its best, the ear can cope with a tremendous range of sound pressures, and sense frequencies from about 15Hz to almost 20kHz. It can readily pick the difference between various instruments playing the same note and sort out the instrumental sounds in a complete orchestra. It can detect changes in pitch of 1 part in 1000, and nominate the direction from which sounds are coming.

A blindfolded person can even form a judgment of an acoustic environment by spontaneously sensing the direction and time delay of echoes.

While human hearing certainly does deteriorate with age and as a result of illness, it nevertheless justifies the considerable effort put into the initial creation of good music and the provision of

Sound Pressure microbars	Typical Sound	Loudness Level decibels
2000	pain threshold	140
200	jet aircraft	120
20	subway	100
2	orchestra	80
0.2	conversation	60
0.02	quiet room	40
0.002	rustling leaves	20
0.002	hearing threshold	0

Table 1: Typical listening situations listed against measured sound pressure levels (left) in microbars, and subjective loudness level (right) expressed in decibels.

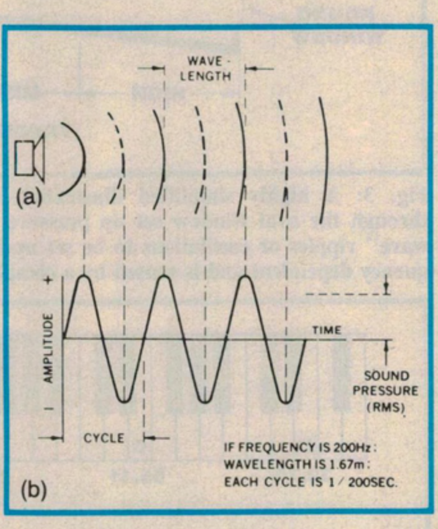

Fig. 1: Depicting a sine wave (b) as radiated from a loudspeaker (a). The diagram illustrates various parameters mentioned in the text: cycle, wavelength, frequency, amplitude and sound pressure level.

Sound waves–how we hear them

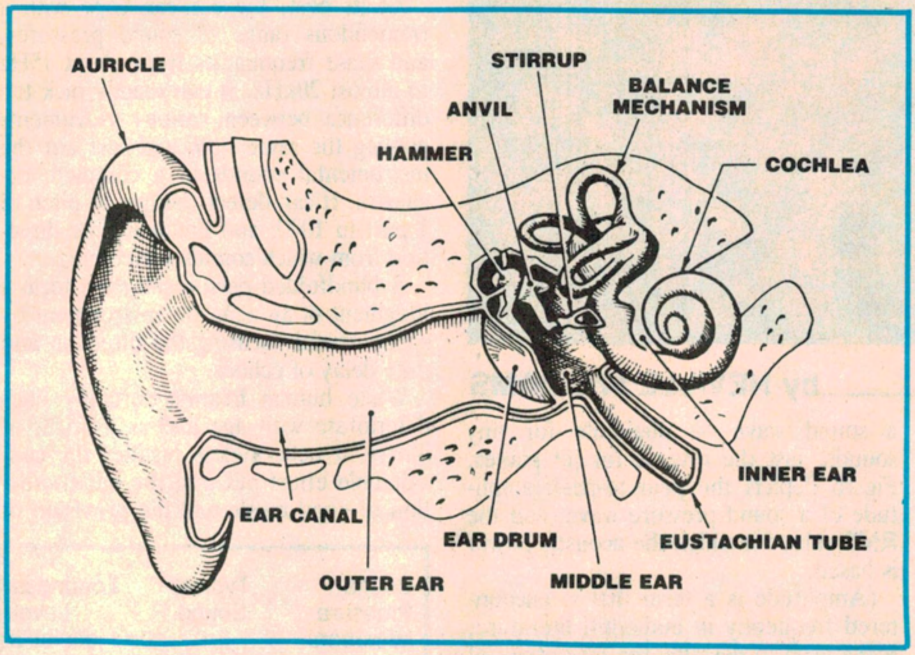

Fig. 2: The human ear comprises three main sections: (1) the outer ear — auricle, ear canal and drum; (2) middle ear — three tiny bones which control the sound vibrations on their way to (3) the inner ear or cochlea — virtually nature's "microphone". Note that the inner ear is also involved in maintaining our sense of balance.

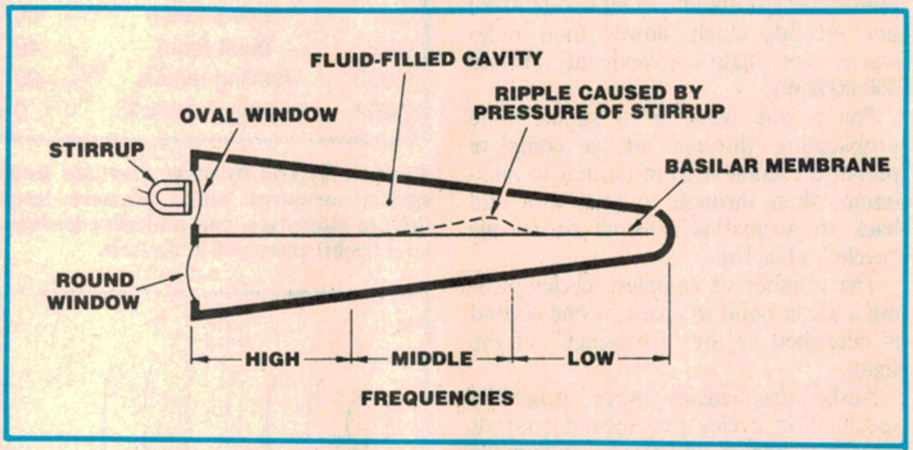

Fig. 3: A highly simplified illustration of the cochlea. Sound vibrations originating through the oval window set up pressure waves in the cochlea fluid, causing "standing wave" ripples or oscillations to be set up in the basilar membrane. Their position is frequency dependent and is sensed by a complex of nerves.

equipment able to record and reproduce it faithfully.

The human ear

The human ear comprises three distinct sections: the outer ear, middle ear and inner ear. The outer ear involves the visible fleshy part, called the auricle or pinna, plus the ear canal and ear drum, as illustrated in Fig.2.

Recent work has confirmed that the auricle or pinna are not just random adornments or nature's fortuitous provision for supporting spectacles! They modify the incoming sound waves in a way which contributes significantly to the ability of the ear to sense direction.

The ear canal is a fleshy tube, open at one end, which functions vaguely like an organ pipe, in exhibiting a modest degree of resonance. It favours incoming sound waves in the region between about 2000 and 5000Hz, tending to increase acuity in the important upper-mid frequency range.

At the inner end of the ear canal is a tough, flexible membrane called the ear drum, which seals and separates the outer ear from the middle ear.

The middle ear

The ear drum vibrates in sympathy with the air column in the ear canal and transfers the vibrations to three tiny bones in the middle ear. Called the hammer, anvil and stirrup (or stapes) the three bones form a lever system which passes the vibrations on to the inner ear, at the same time providing a measure of impedance matching between the two.

A system of involuntary muscles controlled from the inner ear acts as a form of automatic volume control to protect this delicate system from damage. When excessively loud sounds are encountered, the muscles readjust the position of the bones slightly and tighten the ear

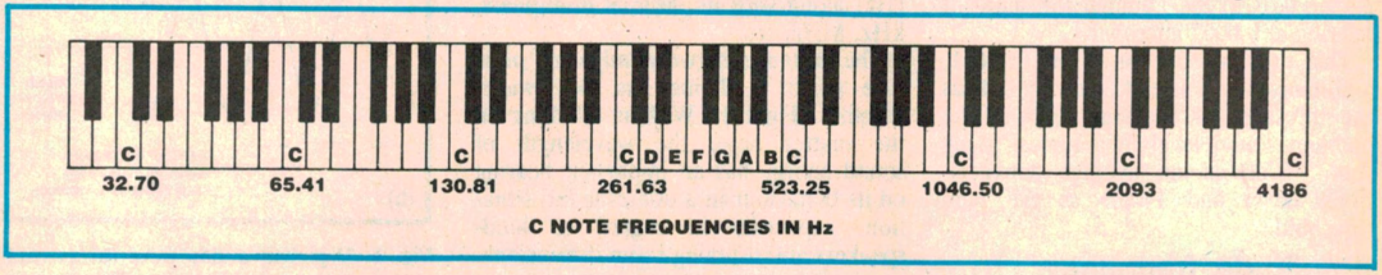

Fig. 4: If you are uncertain about the relationship between frequencies in Hertz and the actual pitch of musical notes, this diagram should help. For standard concert pitch, middle-C has a frequency of 261.631Hz. Note that the frequency of each semitone increases by a factor of about 1.06.

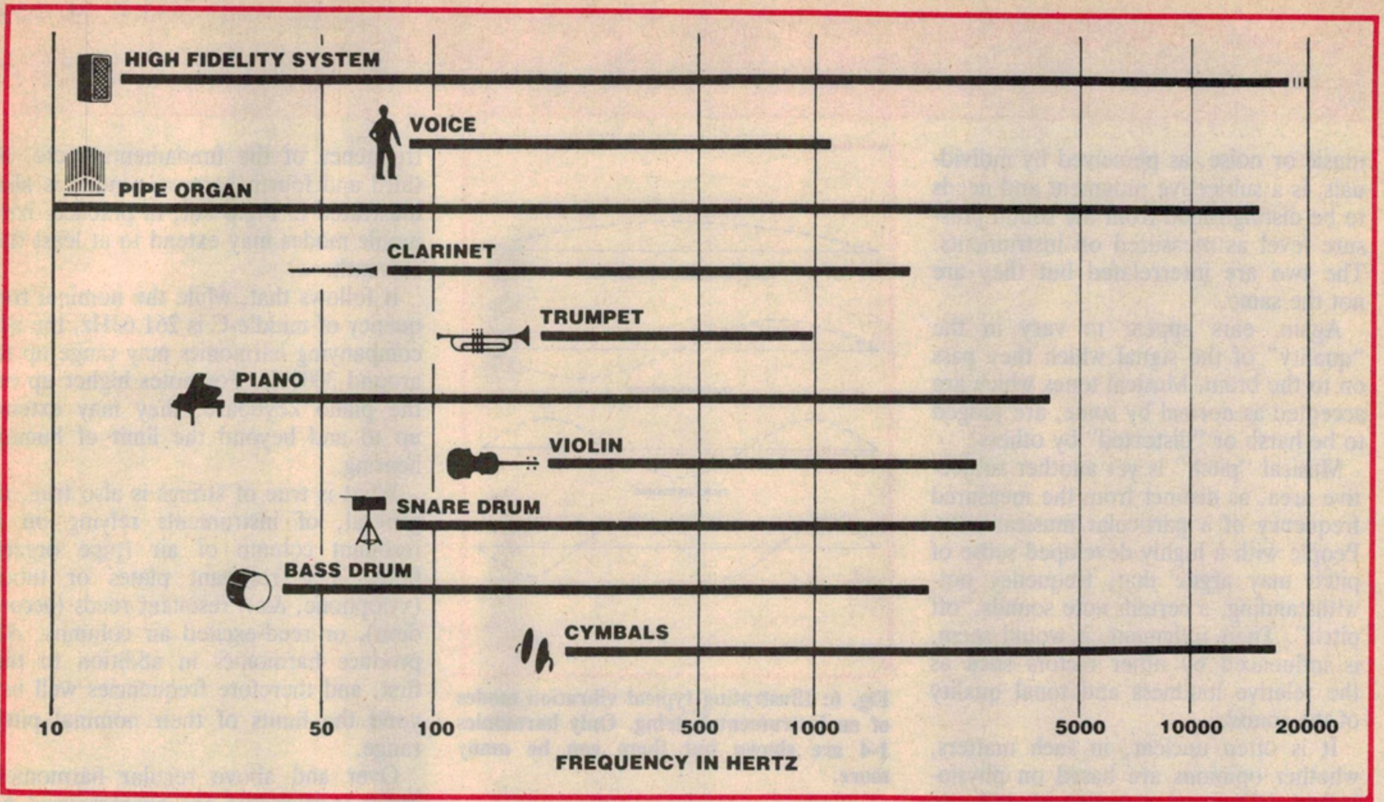

Fig. 5: Musical instruments would be a dull lot if the only frequencies they could produce were within the confines of their formal music range. In fact, their sound is enriched by an array of harmonics, plus other subtle non-harmonic sounds.

drum so that less of the vibration energy gets through to the inner ear.

While the provision is effective in most ordinary situations, it does little to protect the ear against continued long-term exposure to excessive noise levels, or against sudden, explosive blasts of sound.

One other point should be made here, which will be better appreciated as we get further into the series: the automatic volume control function of the ear appears to operate at a sub-audio rate. Thus, while it can adjust the sensitivity to accommodate a variety of prevailing sound levels, the logarithmic control characteristic does not greatly affect the shape of individual audio waveforms.

It therefore does not produce gross aural distortion, as is sometimes suggested. In this respect, the control characteristic of the ear finds a parallel in a variety of variable gain electronic circuits.

The inner ear

As illustrated in Fig.3, sound vibrations are transferred by the stirrup of the middle ear to what is effectively a second diaphragm — the so-called "oval window" of the fluid-filled cochlea.

To-and-fro vibration of the oval window causes waves of fluid pressure to sweep the length of the snail-shaped cochlea, creating "standing wave" ripples in the (basilar) membrane. These, in turn, are sensed by an intricate system of nerves.

Ripples occur at different points along the membrane, depending on the frequency of the incoming sound wave(s) and only nerves which are near the crest are stimulated, thus accounting for the ear's ability to sense frequency.

The inner ear is the "microphone" of the hearing mechanism, in the sense that it converts sound vibrations into neural signals. There the comparison lapses, however, because nerves by their very nature deal in pulse-type information rather than a smooth, electrical replica or analog of the sound envelope.

The fact that the brain can interpret a pattern of sound as complex as that from a full symphony orchestra, plus a choir and/or a grand organ, becomes all the more amazing when it is realised that, in the process, the information has been neurologically pulse-encoded and decoded!

A subjective skill

Most people are born with the potential to hear and interpret sound but the actual ability to do so has to be learned by experience, from birth. Like any other learning process, it is subject to a variety of factors, both physical and environmental.

As already suggested, some people's ears are able to sense a wider range of frequencies than others, but the ability can be curtailed by age, physical ailments, or prolonged exposure to excessive levels of sound — a hazard that has been historically greater for men than women.

To complicate matters further, hearing loss can affect one ear more than the other, causing a degree of unbalance which the brain may not be able to compensate. When this occurs, the ability to sense the direction of sound is impaired, along with the facility to concentrate on a particular sound in a noisy environment. It becomes more difficult, for example, to follow a conversation in a crowded room.

People differ also in their ability to tolerate high levels of sound, with the advantage, this time, appearing to favour men. Certainly, most complaints about music being excessively loud, to the point of physical distress, seem to come from women.

But men and women alike tend to condemn most readily, as too loud, sound which they happen not to like, indicating something other than a purely physical reaction.

Certainly, the "loudness" of speech or

music or noise, as perceived by individuals, is a subjective judgment and needs to be distinguished from the sound pressure level as measured on instruments. The two are interrelated but they are not the same.

Again, ears appear to vary in the "quality" of the signal which they pass on to the brain. Musical tones which are accepted as normal by some, are judged to be harsh or "distorted" by others.

Musical "pitch" is yet another subjective area, as distinct from the measured frequency of a particular musical note. People with a highly developed sense of pitch may argue that, frequency notwithstanding, a certain note sounds "off pitch". Their judgment, it would seem, is influenced by other factors such as the relative loudness and tonal quality of the sound.

It is often unclear, in such matters, whether opinions are based on physiological differences or acquired skills, or both, but one thing is certain: Our reaction to sound is individual and subjective; we each hear things a little differently from our neighbour — a fact which undoubtedly enlivens debate about audio-hifi topics!

And so to music:

It was stated earlier that young, healthy human ears can typically sense frequencies from about 15Hz to just under 20kHz. To convey some idea of what various frequencies sound like, Fig.4 shows the frequency of various C notes on a piano (or on an organ using what is described as an "8ft" voice).

Fig.5 depicts the nominal frequency range of various well known instruments, and here a word of explanation:

If the frequency scale along the bottom of the diagram looks strange, it is because it conforms to the normal practice of plotting audio frequencies on a logarithmic scale. It opens up the important bass region and puts the middle or voice frequencies in the centre, without unduly crowding the treble end.

For instruments which produce discrete musical notes (e.g. organ, clarinet, trumpet, piano & violin) the frequency range depicted in Fig.5 refers purely to what is known as the "fundamental" or "first harmonic", or the basic musical pitch of the physically available notes. Those on the piano keyboard cover a freqency range from just under 30Hz to something over 4000Hz (or 4kHz).

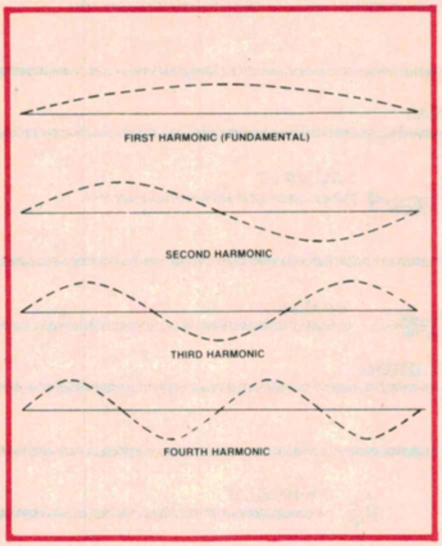

Fig. 6: Illustrating typical vibration modes of an instrumental string. Only harmonics 1-4 are shown but there can be many more.

Harmonic modes

There is more to it, however. When strings are struck (as in a piano), plucked (as in a guitar) or otherwise excited (as in the violin family) they tend to vibrate in a quite complex manner, as illustrated in Fig.6.

In the fundamental (or first harmonic) mode, the string vibrates or oscillates as a whole with respect to the two fixed ends — this at a frequency determined mainly by its physical mass and the tension to which it is subjected. In so doing, strings generate sound waves at the fundamental frequency: 261.63Hz in the case of middle-C.

But there is also a tendency for the two halves to oscillate simultaneously around the centre point, producing a "second harmonic" at about twice the frequency of the fundamental note. A third and fourth harmonic mode is also illustrated in Fig.6 but, in practice, harmonic modes may extend to at least the eleventh.

It follows that, while the nominal frequency of middle-C is 261.63Hz, the accompanying harmonics may range up to around 3000Hz. For notes higher up on the piano keyboard, they may extend up to and beyond the limit of human hearing.

What is true of strings is also true, in general, of instruments relying on a resonant column of air (pipe organ, flute, &c), resonant plates or tubes (xylophone, &c), resonant reeds (accordion), or reed-excited air columns. All produce harmonics in addition to the first, and therefore frequencies well beyond the limits of their nominal pitch range.

Over and above regular harmonics, many instruments are characterised by subtle non-harmonic noises of their own: the air noise of a pipe organ or flute; the thud of hammers or the click of plectra; the buzz of reeds; the scrape of bows — noises which can be acceptable or objectionable, depending on the merits of the instrument and the player.

Memorised, over the years, these harmonics and sounds provide the basis on which we recognise the various instruments — along with members of the percussion family: the bass drum, the timpani, snare drum, cymbals, triangle and the rest.

Wave "envelope"

Out of all this, certain puzzling but quite legitimate questions may occur to the reader:

Considering just one typical note from one typical instrument, with a dozen different frequencies present, plus those

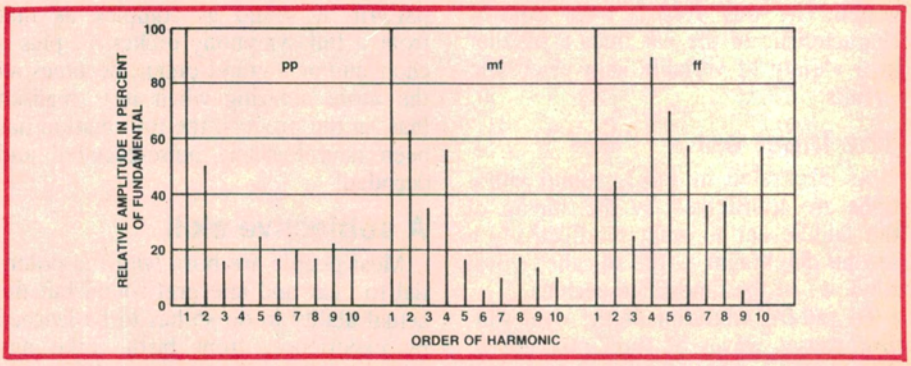

Fig.7: Harmonic analysis of middle C played on a piano at three loudness levels.

"subtle non-harmonic noises" . . .

How can one's ear drum follow a dozen or more frequencies simultaneously? How can it be doing a dozen or more things at the one time? And how can it possibly respond to fifty-dozen frequencies simultaneously from an orchestra or a choir?

The short answer is that ear drums cannot follow a multitude of frequencies simultaneously, or be moving in several different directions at once. Nor do they need to — fortunately!

While an instrument may indeed be producing many frequencies simultaneously, at any given instant, at a single point in space, the individual sound pressure waves can only add up to a single pressure resultant.

At the next instant — and the next — the resultant may be static, or increasing or decreasing; it can't be doing more than one thing at one time. So, if your ear drum happens to be at that reference point, it will simply be responding to the instantaneous resultant — frequently described as the sound pressure "envelope".

Fig.8 shows typical sound pressure resultants or "envelopes" from a violin, trumpet and clarinet, plus one from random noise. The amazing fact is that, if presented with such a sound envelope, the human brain can discern the component frequencies and identify them with a particular instrument; or as just plain noise!

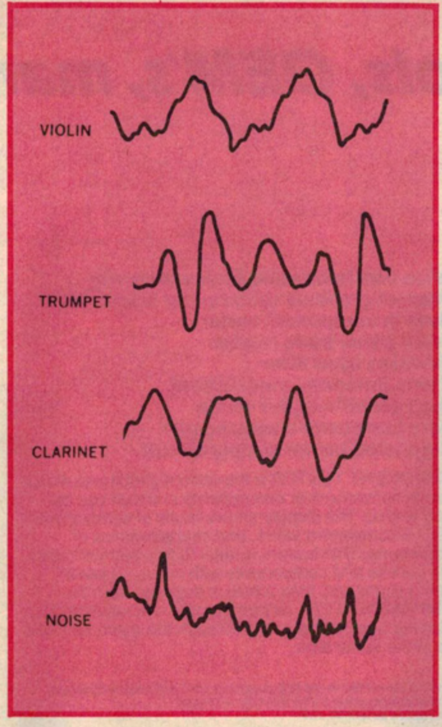

Fig. 8: Typical waveforms that might be presented to the ear, either directly or from a loudspeaker. Although just a scrawl to the eye, they can be resolved by our hearing into frequency components characteristic of the source.

And even if the envelope is that instantaneous pressure resultant from a complete symphony orchestra, with or without an associated choir or orchestra, plus building reverberation, the brain can still sort it out!

Fortunately, for the audio-hifi industry, the introduction of a recording and amplifier chain does not upset things. The microphones translate a pressure envelope into an electrical envelope or resultant, which is then recorded, reproduced, amplified and transformed back into a pressure envelope by the loudspeakers.

If the shape of the sound pressure envelope survives the procedure without being unduly degraded, we can enjoy performances by the greatest artists and the greatest orchestras in the world — some of them no longer with us.

But, for that to be the case, it is essential that the entire recording, reproducing and amplifying chain be as near to perfect as technology and finances will allow. And, really, that's what high fidelity is all about!