III. THEORY

Acoustic Function of the Steel Pan

This section presents measurements and theoretical models from my research on the steel pan. The presentation is complemented by some speculations on the relation of the measured data and the models to the practical tuning work and the design of the steel pan. Since my research only has been going on for a short time, this section is still a bit thin, raising many questions that have to be left without answers.

It is not necessary to read this section to use the handbook for steel pan making and tuning. But if you are curious and want to know why you have to perform the various steps during the making of a pan, this part may provide some explanations. For the experimenting panmaker, this section is intended to provide some theoretical insights to guide the further development of the tuning techniques and the instrument.

To be able to discuss the theoretical aspects of the steel pan later, the section begins with a chapter on music acoustics.

19. Music acoustics

SOUND

Physically, sound is defined as small, periodical variations – vibrations – in the air pressure. The pressure variations are produced by small differences in the density of the air. The vibrations are transferred to the air when a vibrating body (such as a musical instrument) pushes the molecules of the air.

A musical sound can be described in terms of three fundamental characteristics: *loudness*, *pitch* and *timbre*.

The loudness represents the perceived strength of a sound and it is denoted by the sound pressure level, which is measured in decibels (dB).

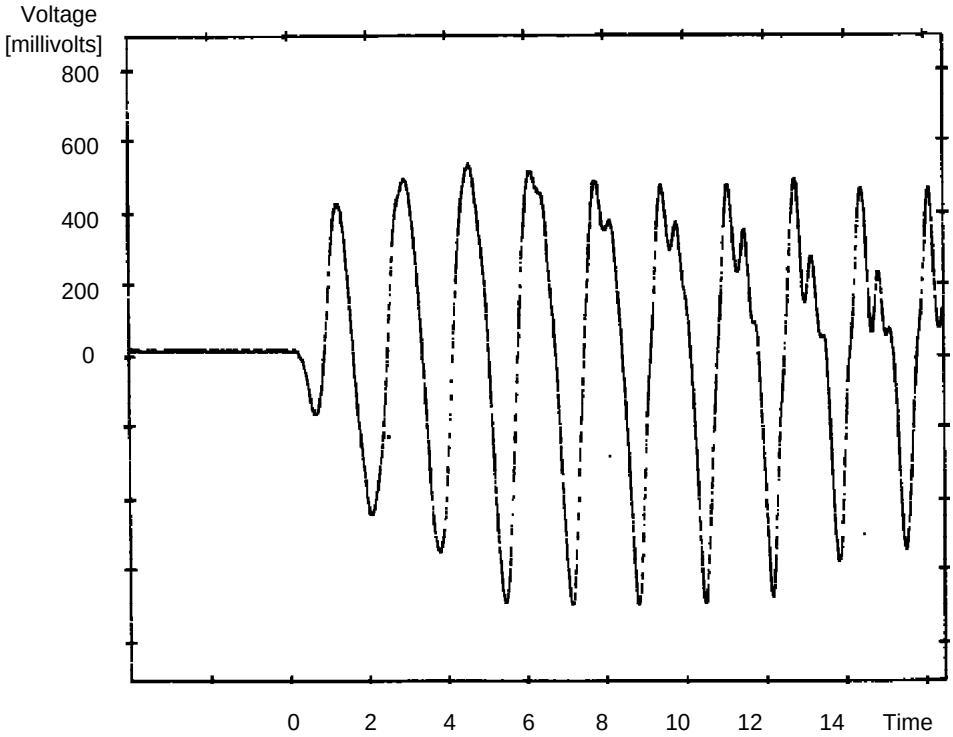

Fig. 19.1 Wave-form of a steel pan tone. (Time measured in milliseconds.)

The pitch is related to the physical measure frequency. The frequency of a sound describes how many times the air molecules are pushed back and forth each second. Frequency is measured in Hertz (Hz).

If the frequency of a single tone is related to its perceived place on a musical scale, the result is called the pitch of the tone. The pitch of a tone is denoted as C, C#, D, D#, etc. If more accuracy is needed, the octave position of the pitch is also included as a number; C1, F#3, G6, etc. The usable range of musical pitches extends from C0 (16 Hz) to C9 (8372 Hz).

The timbre of a sound is a much more complicated characteristic than the loudness and the pitch. It describes the tone "colour" – the character of the sound, and there is no single physical entity that can describe it fully. The timbre can roughly be described by the wave-form, as seen when analyzing the sound with an oscilloscope, see fig. 19.1. The more rugged the wave-form, the more brilliance and treble in the sound.

Musical instruments usually produce simultaneous vibrations of several different frequencies, which are added together to form what is called a *complex* tone. The parts of a complex tone are called *partials*.

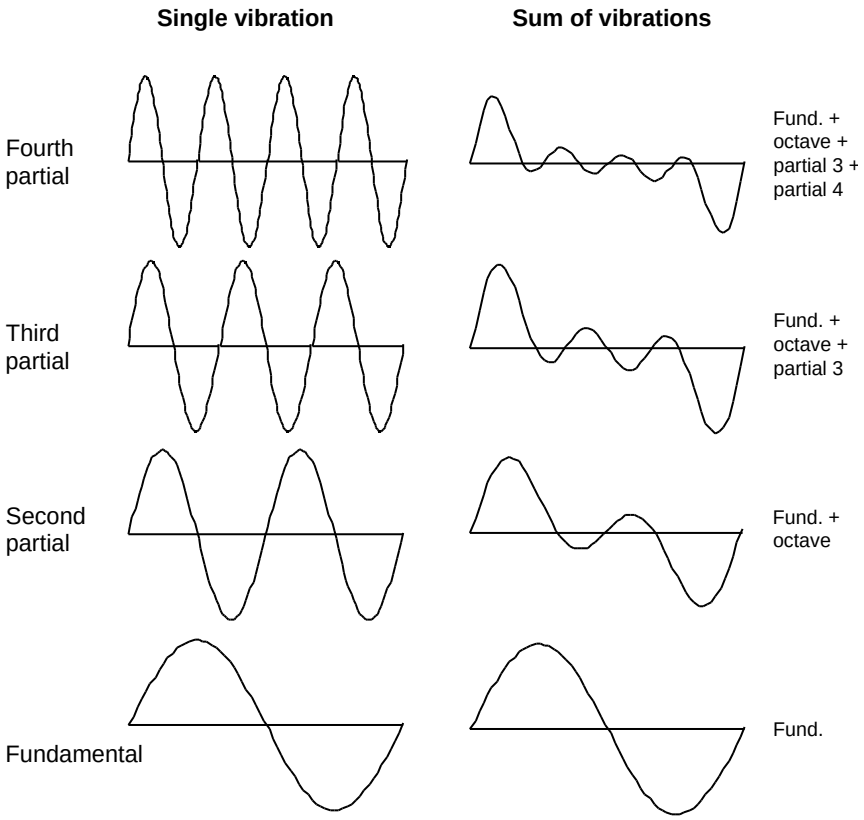

Fig. 19.2 Adding of partials in a complex tone.

Each partial is emanating from a vibrational mode of the instrument (see below). The partials are numbered one, two, three, etc., from bottom to top. Fig. 19.2. shows the resulting wave-form when several partials are added together to form a complex tone.

The process of dividing a complex tone into its individual partials is called a *spectral analysis*. Nowadays, computers can do a spectral analysis in a matter of seconds. The result of a spectral analysis is a diagram, showing the frequency and the relative intensity of the partials. This is called a frequency spectrum, or a *spectrogram*. The spectrogram can reveal a lot about the timbre of the sound. Fig. 19.3 shows a spectrogram of a typical steel pan note.

A complex sound that is perceived as a tone is usually built up of a number of partials that are equally spaced on a frequency scale. This means that the frequencies of the higher partials are multiples of the lowest one. This is called a harmonic series, and the tone is therefore called a *harmonic* tone. Most musical instruments generate harmonic tones. As an example, a harmonic steel pan tone with the lowest partial

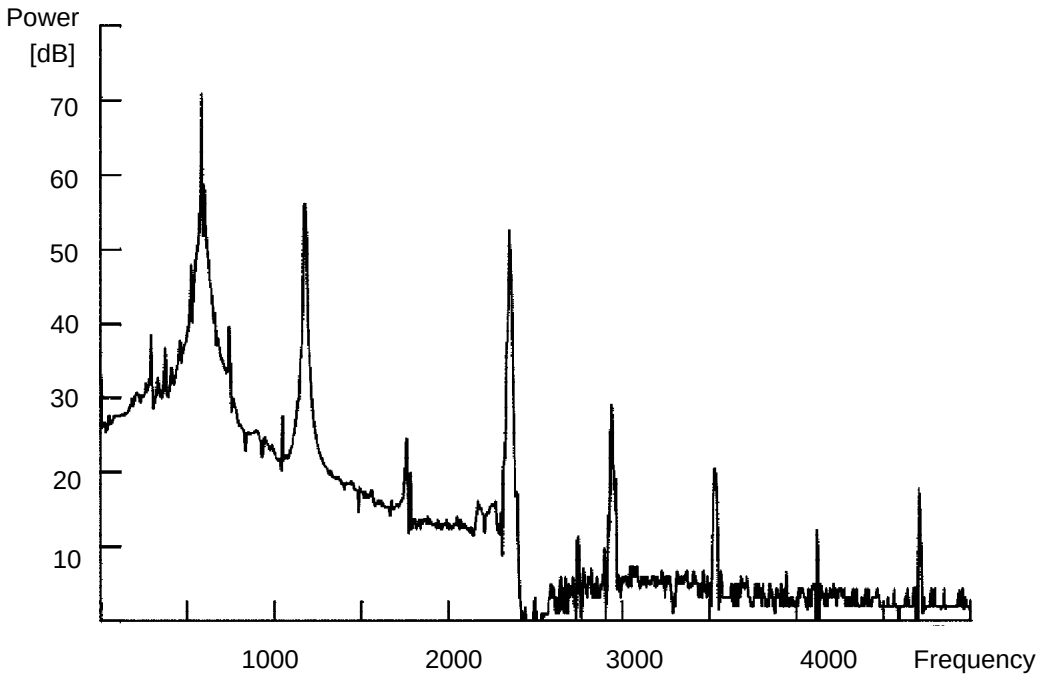

Fig. 19.3 Frequency spectrum of a steel pan tone. (Frequency in Hertz.)

at 200 Hz has upper partials at 400, 600, 800, 1000, 1200 Hz, and so forth.

When we listen to a complex tone, we unconsciously analyse the sound and split it into its partials. The lowest partial of a harmonic sound is what we perceive as the pitch of the tone, i.e., the note's position on the musical scale. Therefore, the lowest partial is called the *fundamental* The higher partials are often called *overtones*to the fundamental.

It is important that the overtones have a harmonic relationship to the fundamental, because we use them to perceptually define the pitch of a complex tone. A sound with many non-harmonic partials will be perceived as dissonant and vague in pitch. Partials that do not fall within the harmonic series are called disharmonic, and do not contribute to the sense of pitch in the tone. Disharmonic partials instead add more character to the timbre of the sound.

VIBRATIONS IN BODIES

The vibrations in a body are generated by two fundamental properties: the *mass* of the material and a *tension*that tends to restore the material to its rest position if it is disturbed. When an instrument is *exited*(hit), the interaction between the mass and the tension will generate sound waves passing through the body.

When the sound waves reach a point of difference in the density of the medium they are travelling in, they are reflected. When the reflected sound wave is travelling back and forth in the body, the sound energy will add at some points and cancel at some other points. This phenomenon is called a *standing wave* In the points where the wave energy cancels, the surface of the body remains at rest. These points are called *nodes* At the points where the energy adds, the body is vibrating fiercely. These parts are called *anti-nodes*

The *resonance* of a body makes it respond with certain standing-wave vibrations when hit. These vibrations are called the *normal modes* (or eigenmodes) of the body. Each normal mode has its corresponding resonance frequency, producing a specific partial in the frequency spectrum of the note emitted from the vibrating body.

PARTIALS

As seen from above, the normal modes of a vibrating body generate partials. The distribution of these partials determines whether the sound can be considered to be harmonic or not; if the partials are evenly spaced, the tone sounds harmonic. To be able to discuss the importance of harmonic partials later, we need to take a first look at their musical significance.

Fig. 19.4 shows an example of the partial distribution in a harmonic tone with a fundamental at 200 Hz.

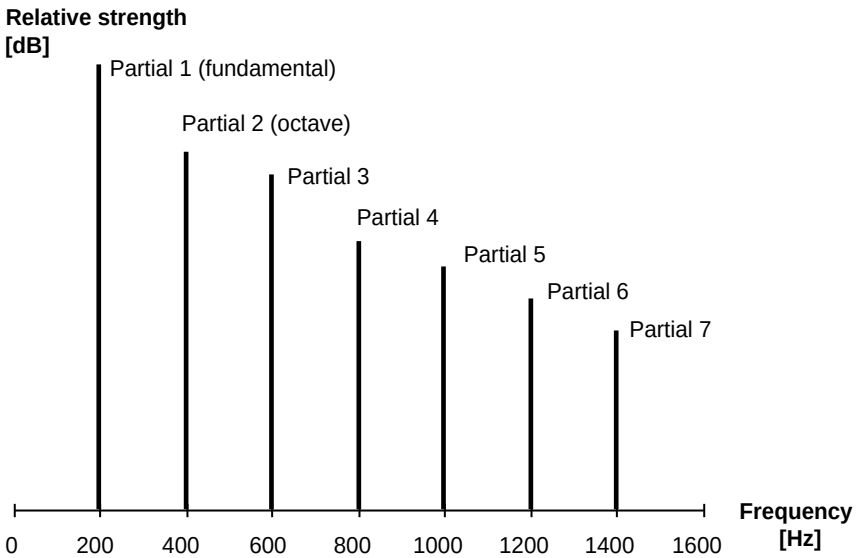

Fig. 19.4 Harmonic partials of a complex tone.

The table below shows how the same partials can be looked upon in a musical situation. The first row shows the partial number, the second its frequency, the third shows the step between two successive partials, and the fourth shows their musical interval related to the fundamental.

Partial	Frequency	Step interval	Interval relation to fundamental
1	200 Hz		Fundamental
2	400 Hz	Octave	One octave above the fundamental
3	600 Hz	Fifth	One octave and a fifth above fundamental
4	800 Hz	Fourth	Two octaves above the fundamental
5	1000 Hz	Third	Two octaves and a third above fundamental
6	1200 Hz	Minor third	Two octaves and a fifth above fundamental

The table shows that the harmonic partials all have a relationship to the fundamental that can be derived from the musical scale. For instance, each doubling in frequency represents an octave step.

Musically, the intervals that sound most harmonic are, in falling order, the octave, the fifth and the third. If another note that has a pitch that is an octave or a fifth above the fundamental sounds together with the hit note, it will fall into its harmonic spectrum and support it. This has implications for the design of steel pans, which will be seen later in the chapter about layout.

MUSICAL INSTRUMENTS

All musical instruments have in common that they convert kinetic energy from the player into acoustic energy, i.e., to vibrations it the air. The player can transfer the energy to the instrument by blowing, bowing, plucking or hitting. In the search for a model of the tone generation in the steel pan, only instruments that are hit – percussion instruments – are of further interest.

Percussion instruments may employ strings, bars, membranes, plates or shells as sources of sound. The listing of instrument types below has been made according to the shape of the vibrating part of the instrument. It represents a scale of increasing complexity in tone generation, leading from the simple string of a guitar to the complex shell of a steel pan note.

String and bar instruments

The string is the simplest example of a vibrating body. The restoring force of the vibrations is supplied by the tension of the string. The

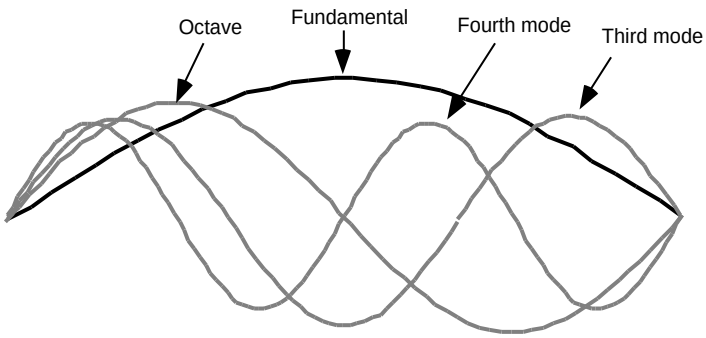

Fig. 19.5 Vibrational modes in a string.

frequency of the string vibrations is determined by three factors: The length of the string – a longer string yields a lower tone. The tension – higher tension yields a higher tone. The mass – a heavier string gives a lower tone. Strings generate harmonic overtones automatically. Fig. 19.5 shows the standing wave patterns of the lowest normal modes in a string.

For musical purposes, a bar may be seen as a string with one new property; its stiffness. The stiffer the material of the bar, the higher the frequency will be. In principle, the bar is acting like a string, but the restoring force in the vibration is supplied by the stiffness of the bar instead of the tension. The partials of bar instruments are not harmonic, but the lower partials can be tuned by thinning the bar at appropriate places. Examples of bar instruments are xylophones, vibraphones or triangles.

Membrane and plate instruments

A membrane may be thought of as a two-dimensional string. The vibration of a membrane is basically the same as the string, but here the vibrations can extend in several directions. In principle, a rectangular membrane acts as two independent strings; one along the length of the membrane and one across it. This means that there will be independent vibrational modes in both the directions, see fig. 20.2.

The partials of a vibrating membrane are seldom harmonic – they depend on the tension and the relative length of the sides of the membrane. Drums are the best examples of membrane instruments.

The next step in complexity is to make the membrane stiff. This yields a stiff plate. Vibrating plates bear the same relationship to membranes that vibrating bars do to strings. The restoring force is produced by the stiffness of the material, instead of the tension. The normal modes for a rectangular plate are approximately the same as for

the rectangular membrane. The partials of a plate are not harmonic.

Shell instruments

Finally, if we make the plate slightly curved, we arrive at a physical shape that resembles a steel pan note. Theoretically, the note dent in a steel pan may be seen as a shallow *shell* "Shallow" here means that the height of the arch is small compared to the size of the dent. The new acoustic factors introduced by the curving of the shell are the rise and the shape of the dent. Further, the fastening of the note in the pan surface makes it possible to introduce a tension in the dent.

The factors affecting the frequencies of the vibrations in a steel pan note represent the sum of all the factors of the less complicated resonators mentioned above, plus the two extra introduced by the arching:

- The size of the note
- The weight of the material
- The stiffness of the material
- The tension
- The rise of the arch
- The shape of the arch

The tension in a steel pan note is presumably not produced by stretching, as in the string. It is rather of a suppressive type, forced into the note when it is lowered during the tuning. According to acoustic theory, a suppressive tension applied on a vibrating body lowers the frequency of the tone. The existence of a tension in the steel pan note is is still to be proved.

The steel pan is classified as belonging to the instrument class of *idiophones*, which means that the pitch is determined by the shape and the internal state of the resonator. There are not any ready-made formulas for the calculation of the vibrational modes in such a complex shape as the steel pan note. A formula would have to include all the variables (factors) mentioned above and would be very complicated.

To entangle the situation further, the tone generation in a steel pan note seems to be very *non-linear* in its nature. This means that the variables involved in the tone generation affect each other in a way that makes it impossible to express the mechanism in a simple formula. For more about the non-linear tone generation, see below.

But some relief is to be found; my studies show that, as a first approximation, the steel pan note may be considered as an almost rectangular plate, disregarding the arching and the tension in the note. This means that the vibrational patterns of a rectangular plate (or a membrane) are to be found in a steel pan note, and that the study of the vibrational modes can be simplified accordingly.

20. Tone generation in steel pans

The shallow dent of a steel pan note is indeed a complicated resonator. No one has so far been able to explain how the steel pan works and why it generates such harmonic tones. As a physicist and a steel pan-player, I got curious and decided to try to find an explanation to the tone generation in the steel pan. Therefore, I started to do some part-time research at the Royal Institute of Technology in Stockholm.

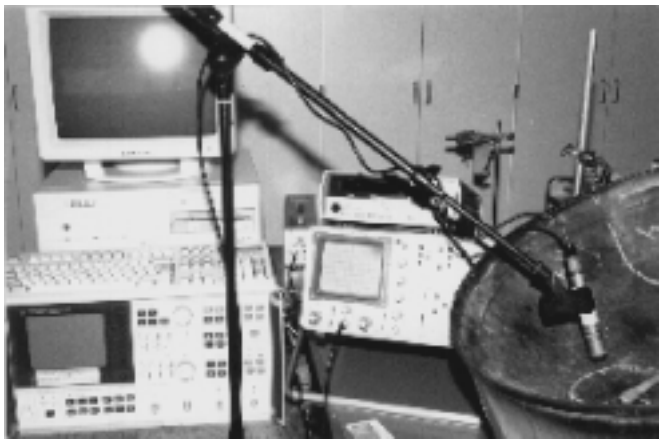

Fig. 20.1 Research on the steel pan. Experimental setup with (left to right) frequency analyser, computer, oscilloscope, frequency counter and microphone.

During the three years the research has been going on, I have made some measurements and I also have some preliminary results. In this chapter I want to present the findings from my work and what ideas and thoughts that will govern my future research on the steel pan.

My research started off with two simple questions:

(A) *How is the unique tone of the steel pan generated?*

(B) *How does the choice of material, design and crafting methods affect the tone?*

To make progress with these two main questions, I needed to know more about both the tone and the instrument. Therefore, I decided to focus my study to three fields:

(1) To register and understand the *acoustic properties* of the steel pan tone.

(2) To register and understand the *construction* of the instrument.

(3) To reveal the *relationship* between the acoustic properties of the tone (1) and the physical properties of the instrument (2).

The discussions with the tuners and the practical section of this book can be seen as main actors in the part of understanding the instrument. The laboratory work that is to be presented in this chapter represents the understanding of the tone. The rest of this theoretical section is a first attempt to explain the relationship between the construction and the tone.

MODES OF VIBRATION

A good steel pan tone has many harmonic partials; at least five or six that are strong relative to the fundamental, see fig. 19.3. The question is, how are these partials generated? If we disregard arching and thickness of the note and look at the note as a membrane, we get some clues to the normal modes generating the partials.

Fig. 20.2 shows a graphic view of standing wave patterns of the lowest three normal modes of a rectangular membrane. The lowest three modes of typical steel pan notes have been measured to be the

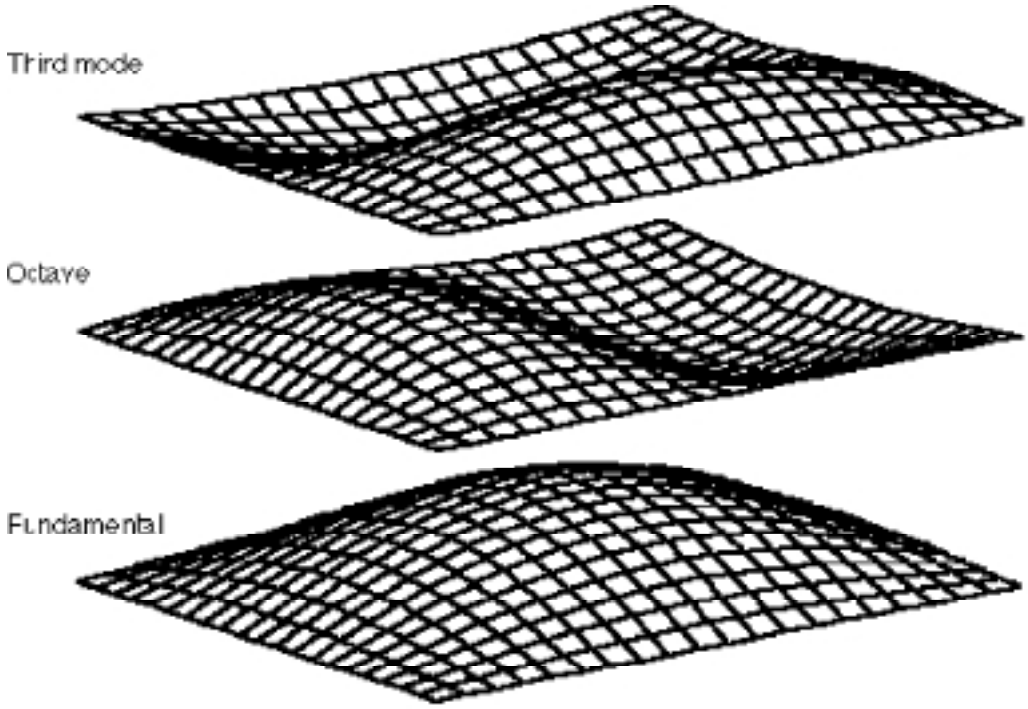

Fig. 20.2 The lowest three normal modes of a rectangular membrane, which are equal to the standing wave patterns of normal modes in a typical steel pan note.

same as these. Fig. 20.3 shows the lowest three modes of a steel pan note, together with cross-sections of the motions along and across the note.

The lowest mode, the fundamental, is easy to understand – the whole note is vibrating up and down like the head of a drum. This is equivalent to the situation in which two hypothetical strings stretched along and across the note would be moving up and down in their whole length, see fig. 20.3.

For the second mode, the octave, the note is vibrating up and down

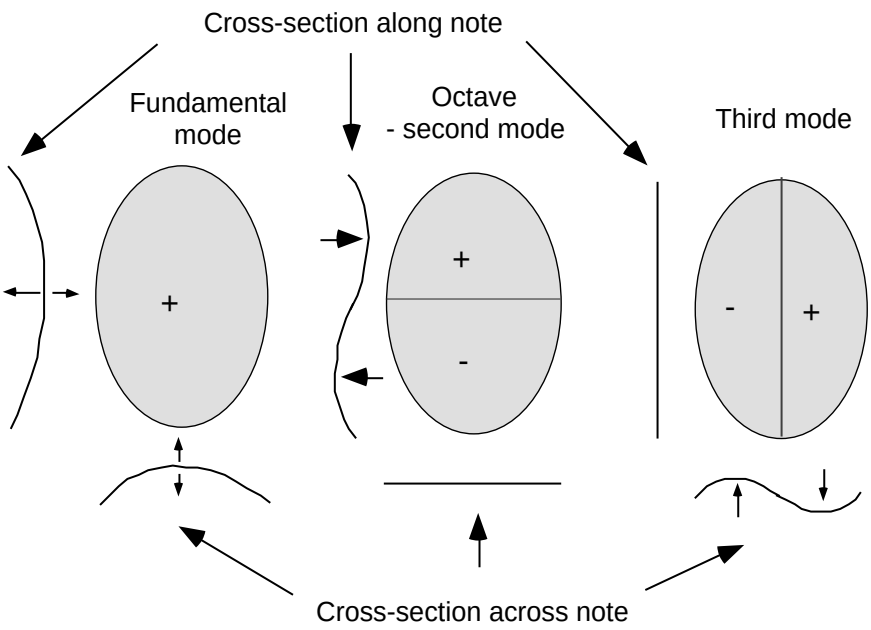

Fig. 20.3 The three lowest modes of vibration in a steel pan note.

twofold along its length. A node line – a part where the surface is standing still – can be found in the middle, see the dotted line in the second note in fig. 20.3. The existence of the octave mode is easy to prove by putting a finger in the middle of the note and striking it at one end. This damps the fundamental and generates a flageolet – the octave sounding alone.

The third partial is generated in the same way as the octave, but here the note is vibrating up and down twofold across. A nodal line can be found lengthwise in the note. This can be proved in the same way as with the octave, but is a bit harder to hear. Put two fingers along the dotted line of note three in fig. 20.3 and hit the note near the side, preferably with the hard end of the stick.

I have measured the frequency of the lowest three modes of several steel pan notes and examined their relation to the lowest three partials in the steel pan spectrum. This is easily done by driving the note at the measured partial frequencies with a tone from a loudspeaker and looking at its mode response. The result can be seen in fig. 20.4.

HIGHER PARTIALS

From the discussion above, we see that the lowest two harmonic partials in the steel pan tone can be explained as generated by the two lowest vibrational modes of the note. But what about the higher partials?

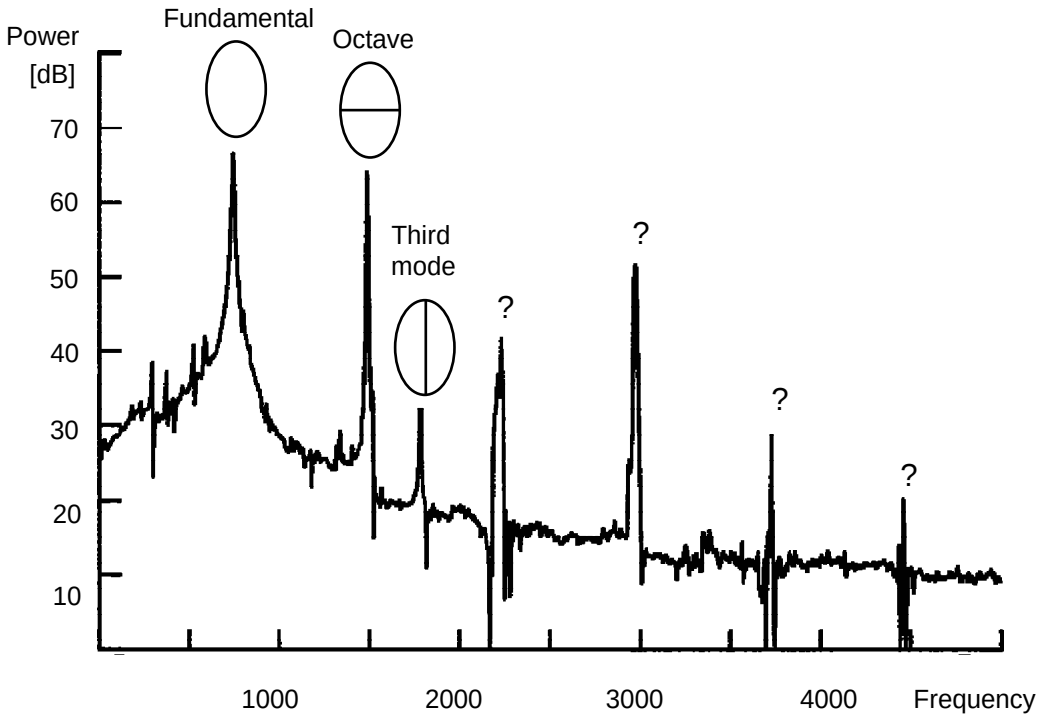

Fig. 20.4 Relation between normal modes and partials in a steel pan note. Nodal lines of the modes indicated above corresponding partial peaks in the diagram. (Frequency measured in Hertz.)

According to the measurements they are present in the tone, but the modal theory does not seem to be able to explain their existence. In fact, the third mode of a steel pan note often generates a partial that not is harmonic, see fig. 20.4. It often sounds with a tone that is one octave plus a third or a fourth above the fundamental.

The theoretical value for the third partial in a harmonic series should be one octave and a fifth above the fundamental. As seen from fig. 20.4, the tone of a steel pan has a partial that matches this harmonic interval perfectly, but it does not come from the third mode of vibration. A suggested explanation of the generation of higher partials can be found in the chapter about non-linearity.

When looking at the onset (the beginning) of a steel pan tone, one notices that the higher partials tend to arrive a bit after the beginning of the tone. My measurements show that they arrive about 20-30 milliseconds later then the onset of the fundamental, see fig. 20.5. In ordinary percussion instruments, the higher partials usually arrive at the onset, together with the fundamental.

The notion that the higher partials tend to arrive later in the steel pan tone suggests that they are not initiated by the stroke. It rather seems that they are generated by some other mechanism that needs a few milliseconds to start working.

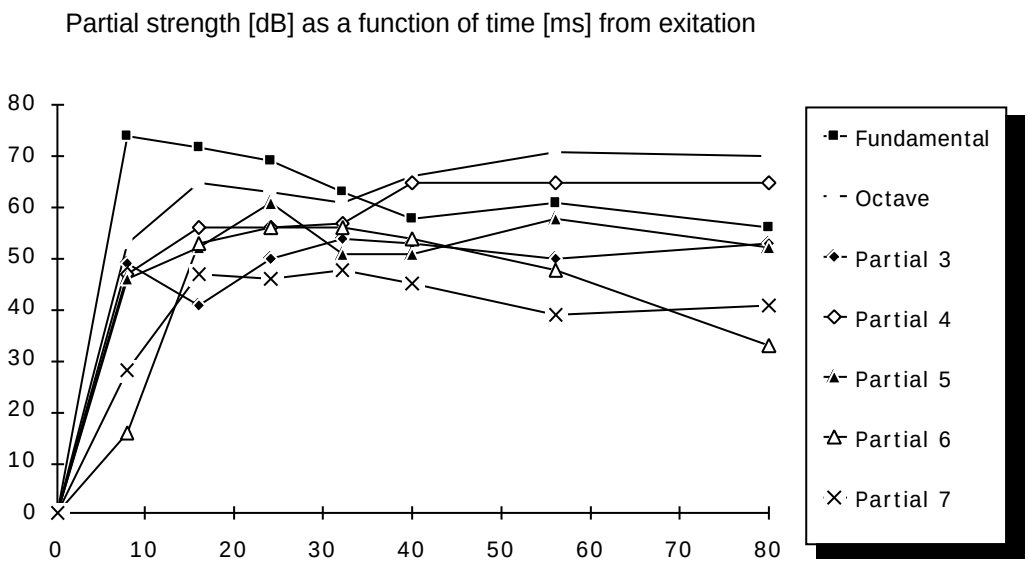

Fig. 20.5 Relative strength of the partials during the first 80 milliseconds of a steel pan tone.

NON-LINEARITY

The contradiction that the frequencies of the normal modes of the steel pan note do not have a harmonic relationship but the frequency spectrum still shows a large number of harmonically spaced partials, reveals that the higher partials must emanate from some other source than the vibrational modes. My hypothesis at this stage is that the harmonic partials are generated by a non-linear ”distortion” process of the vibrations in the note, but this still has to be fully explained and proved.

The non-linearities may be introduced in the tone generation by the shape of the note and its tension. These properties will make the note move asymmetrically when it is vibrating, probably moving a bit easier and farther upwards than downwards. If the note moves asymmetrical, the vibration of the fundamental will also start to generate overtones.

This would explain why the higher partials arrive later: Only the lower normal modes are exited by the stroke and the higher partials are then generated later by the shifting of energy from the fundamental mode to higher frequencies.

This non-linear ”distortion” process may be compared to the situation where a pure sine wave is the input to an amplifier that tries to output it beyond its range of power. The output tone will then exhibit

harmonic overtones. You might say that the fundamental mode of the note acts like a sine wave, but it is forced to generate overtones by the asymmetric shape and tension of the note.

To speculate further, it seems as if the harmonic spectrum of the steel pan tone is generated by some intricate interaction between the non-linearities of the fundamental and the octave mode. The octave mode of the note also generates a series of harmonic overtones when it is vibrating. These overtones will be equally spaced over the frequency axis, but with an interval that is equal to the frequency of the octave. If the fundamental has a frequency of 200 Hz, the octave will be at 400 Hz. Then the partials generated by the octave mode will be found at 800 Hz, 1200 Hz, 1600 Hz, etc. This means that they will coincide with every second overtone of the fundamental. The cooperation between the harmonic spectra of the fundamental and the octave would explain why the partials with even numbers (2, 4, 6, etc.) are stronger than the odd numbered partials, see figures 19.3 and 20.4.

If a proper harmonic spectrum is to be generated, the octave has to be tuned to a perfect two-to-one relationship to the fundamental. If the octave is only a few *cents* (100 cents equals a half-tone interval) away from its exact value, the sound of the note will be dissonant. This can also be seen in the spectrogram, which will show a tone with double partial peaks, see fig. 20.6

My thoughts about the generation of higher partials have eventually led me to form a working-hypothesis. The following is a conclusion of the hypothesis that will govern my future research on the steel pan, together with some measurements that support it:

> Hypothesis regarding the mechanism for generation of harmonic partials in steel pans
>
> *"The harmonic partials above the octave in a steel pan tone are not generated by vibrations of the higher normal modes of the note, but by a non-linear process involved in the motion of the fundamental and the octave modes."*

The measurements supporting the hypothesis are:

1. The frequencies for measured normal modes of order three and four do not fall into the harmonic spectrum of the tone. Mode three is sometimes too high, sometimes too low, seldom in the harmonic spectrum. Mode four seems to be most often too high. Measured harmonic partials, on the contrary, are all spaced with exactly equidistant intervals.
2. After striking the note, the fundamental reaches its maximum

within a few milliseconds (ms) and the octave within 15 ms. The higher partials reach their peaks after 20-30 ms. This indicates that the higher partials are not generated by the stroke.

3. A note driven by a pure sine wave at the frequency of the fundamental responds by emitting a tone containing a large number of harmonically spaced partials.
4. If the frequency of the driving sine wave is varied, the higher partials are more sensitive to these variations than the fundamental and the octave. A variation of ± 2 Hz gives as an average a 30 dB difference in the higher partial level, whereas the corresponding difference for the fundamental and the octave is about 10 dB.

More focused measurements in the future and the development of a refined model will have to reveal if this hypothesis can be considered to be valid for the tone generation in steel pans.

Non-linear effects are present in all instruments but so far the acousticans have paid little attention to them because the tone generation of regular string and wind instruments can be explained fairly well by linear models. But to the steel pan, the non-linearities seem to be the foundation of the tone generation. Therefore, my belief is that a future

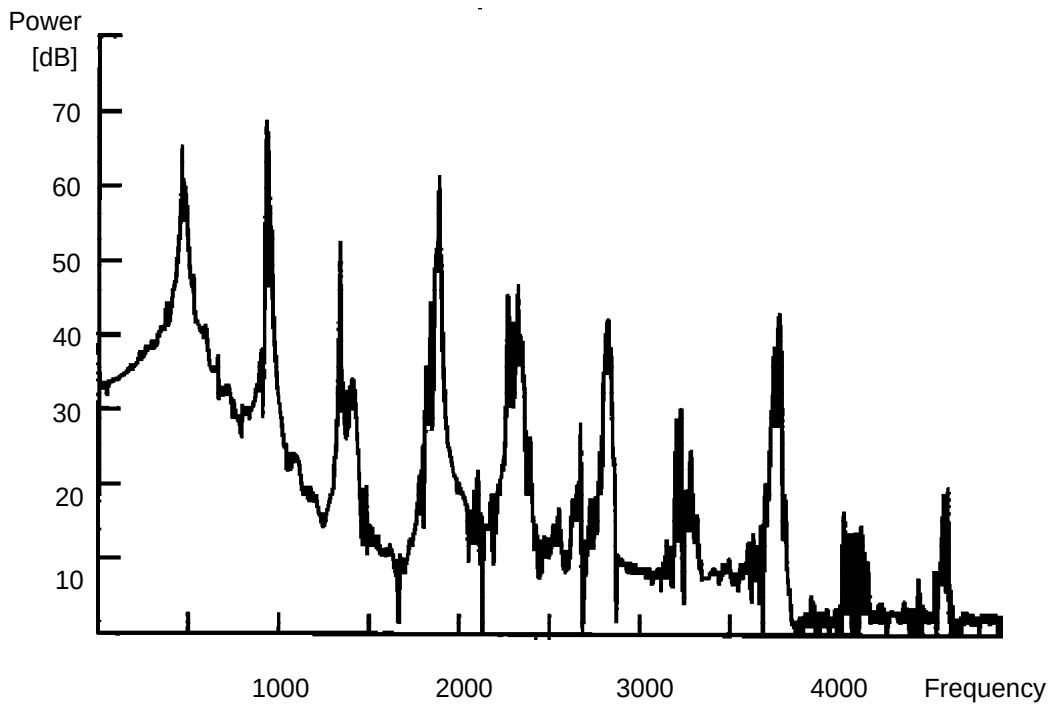

Fig. 20.6 Spectrogram of a dissonant steel pan tone. (Frequency measured in Hertz.)

theoretical model of the tone generation in steel pans has to be non-linear.

The final notion will be that – whatever the mechanism – the tone generation in the steel pan does not work like any other tonal instrument. The only instruments that seem to have a similar tone generation are cymbals and gongs.

21. Material

Just as it is important to choose the right wood for string instruments, the metal is important to the steel pan. The choice of metal is even more crucial for the pan, as the steel is the primary source of the sound in the pan, not only acting as an amplifying resonator as the wood of string instruments.

QUALITY

First, the quality of the metal is vital to steel pan fabrication. The steel that is used for the drums is a compound that, besides the iron, contains small amounts of carbon (0.1-0.2%) and manganese (0.4-1.4%). The concentration of these added substances determines the mechanic and acoustic properties of the steel.

One major problem for the community of panmakers seems to be their lack of control over the raw material. The reason is that, during the evolution of the pan, the tuning has come to put more extensive requirements on the steel quality than the drum's original purpose as a container does.

A first step towards a solution to this problem would be to analyse the metal of a well-sounding instrument. A documentation of the exact content of carbon and other substances in the steel would be of good help in the choice of raw-material. I have taken some samples, but I have not had the opportunity to analyse them yet.

The next step would be to get a steel mill to deliver raw material according to this specification and have a steel drum factory to produce high quality drums especially for steel pan making.

Further measurements, stating within which ranges the content of the various substances could vary and still make a good instrument, could also give clues to which factors in the properties of the metal that are important to the tone generation.

THICKNESS

The thickness of the steel affects the resonance frequency of the note. Thicker metal is stiffer and therefore it produces a higher pitch in a note with constant measures. But thicker metal is also heavier. This lowers the frequency, which will counteract the effect of the stiffness. The acoustic effect of changes in thickness has to be measured to reveal what the net result will be. Suitable experiments would be to add chromium or grind off material successively and do measurements of the frequency spectrum.

Another important acoustic effect of the thickness is that an increased mass can conserve a larger amount of energy. Notes with thicker metal can take harder hitting without ”breaking” in sound. This means that they are capable of receiving and radiating more sound energy – the instrument will be more powerful.

But thicker metal also means that it will be more difficult to get the notes to vibrate – to excite them, which can result in a problem for the small notes in tenors and double tenors. Measurements show that the sinking of a tenor makes the metal about 30% thinner in the middle. The thinning in the middle is of benefit for the higher note that will be located there, because the reduced stiffness will make it easier to get them to vibrate. This might be one of the reasons for sinking the higher pans deeper and putting the higher notes in the middle.

CRAFTING

The acoustic effects of the crafting work are shaping the metal, making it softer and forcing tensions into it. The softening of the metal occurs because the initial crystal structure of the metal is destroyed when it is re-shaped. A new crystal structure is later established by the tempering, and this restores some of its former hardness.

One reason for doing the backing, besides the shaping of the note dents, could be to force a tension into the notes by compressing the metal in them. This possible tension could later be conserved by the groove in the metal and by the tempering. If there is a conserved tension introduced by the backing, it would presumably result in an expansion force, acting to push the sides of the note outwards. According to acoustic theory such a tension lowers the pitch, see the chapter about tone generation above.

If the effects of the manual crafting work could be neglected, it would be possible to use machines and do the sinking and the backing with mechanised methods. The sinking has already been mechanised

at MIC – Metal Industries Corporation, and some claim that it works, while other say the opposite.

It is practically impossible to do any laboratory experiments on the acoustic effects of the crafting. Future field experiments will have to determine if it is possible to press-form the whole pan.

TEMPERING

Another source of problems for the tuners seems to be the rather uncontrolled method for tempering and the lack of theoretical knowledge of what happens to the metal during the heating. The most important effects of the tempering are presumably an anneal (removal of tensions) and a hardening.

The crafting introduces many tensions and local differences in hardness in the metal due to an effect that is called a *cold-hardening* When the metal is hit with a hammer it gets hot in the spot where it is hit. But the heat is quickly led to the surrounding metal, which results in a fast cooling of the heated spot, which has a hardening effect.

The most significant effect of the tempering is presumably the anneal, which removes this cold-hardening and the uneven tensions put into the metal during the grooving and the backing. If they were left, they would disturb the delicate physical conditions in the note and make proper tuning impossible. The anneal should result in notes with an even tension over their whole surface. This anneal is presumably the main reason why quality steel pans can't be made without heating.

Beside the anneal, the steel also seems to be affected by two other processes during the heating: First, it is hardened by the reorganization and fixation of the new crystal structure in the metal by the heating and the cooling. Second, there seems to be an oxidation of some of the carbon content of the steel, making it more stretchable. Carbon is initially put into the steel to make it hard.

The most critical part of the tempering is to balance the two processes against each other. If the pan is heated too little, it will not be tempered enough, making it soft and unstable during the tuning. This problem can be solved by heating the pan again, this time a little longer.

If the pan, on the other hand, is heated too long, too much of the carbon will oxidise, making the metal too stretchable and thus impossible to tune. Unfortunately, there is no way to redo the tempering if the pan is burned too long. The existence and the acoustical significance of these two processes have to be investigated further by analysing the metal before and after the heating.

The next vague point of the tempering is the cooling of the pan. Some tuners use water, some use oil, but nowadays most tuners don't seem use anything at all. They just let the pan cool by itself in the air.

People that are knowledgeable about metals tell me that it is impossible to temper without using any cooling liquid. This would only result in an anneal. But the tuner doing the practical work knows that the pan feels harder after the heating. This is a contradiction that needs to be investigated further in cooperation with metallurgists.

Future solutions to the present problems would be: First, an investigation of what happens in the metal during the tempering. Second, measurements of a properly done tempering. Third, development of a controlled tempering method, such as the use of an oven.

22. The "sink"

There are at least three acoustic reasons for sinking the bottom of the drum: First, to remove the low tone in the bottom. Second, to make the metal thinner in the middle where the highest notes are to be put. And third, to make an overall curvature that is suitable for the notes of the different pan types.

The most obvious acoustic reason for sinking the bottom of the drum to a round basin is that the spherical shape has a very high resonance frequency related to its size. This means that any tones generated by vibrations in the sunk bottom will be well above the pitch of the notes.

The deeper the pan is sunk, the thinner the metal will be in the middle. Thinner metal is presumably beneficial for the tone generation of the higher notes, see the chapter about material. This may be one of the reasons why small notes in the outer ring often sound poorly and higher notes usually are put in the middle.

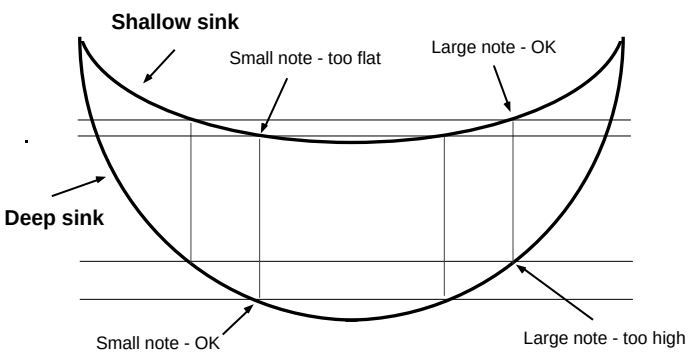

Fig. 22.1 Relation between sink shape and note height.

There also seems to be a certain relationship between the size of the notes and the

needed overall curvature of the pan – small notes need a rounder arch of the sink while large notes need shallower sinking to get the right height. If a large note was made in a pan that is deeply sunk, its arch would presumably be too high to generate a good steel pan tone, see fig. 22.1.

The intricate relation between the shape of the sink and the note size is presumably due to the very special, cylindrical shape of the note dents. When elliptical notes are shaped in the sunk concave surface, the resulting note arch will be cylindrical with its largest curvature across the note. The length axis of the note is almost flat, a result that well coincides with the fact that most of the partials are generated from vibrations along the length axis of the note, see fig. 24.3 and the discussion of note arch further down.

23. The groove

When a steel pan note is vibrating, some of its vibrational energy is transmitted into the air and to the rest of the pan, but the main part is reflected back and conserved in the note. The acoustic purpose of the groove seems to be to provide this conserving mechanism. Tuner Denzil Fernandez says: ”The purpose of the grooving is to create boundaries where-by a transverse wave can be generated and trapped within the region of each boundary.” This notion seems to be in accordance with acoustic theory.

The groove presumably introduces a local difference in what is called the acoustic *impedance* of the metal. The acoustic impedance is a property of the metal that describes how difficult it is for sound waves to travel through it. The harder the material, the faster and easier the sound waves travel, and the less the impedance. The grooving ”breaks” the crystal structure of the metal and makes it soft, forming a ”joint” that acts as an acoustic impedance barrier. When the vibrational impulses in the note reach the barrier they are reflected back into the note.

GROOVE HARDNESS

Harder grooving will presumably result in an increased difference in the acoustic impedance. This will result in a more effective reflection, which means that less acoustic energy will leave the vibrating note. The less the amount of energy that is lost to the surroundings, the longer and weaker the tone will be.

The bore pan, presented in the section about developments, presents a way to study the effect of the groove joint: If the holes are made closer to each other the border will be softer. Denzil Fernandez' experiments show that this makes the tone longer and weaker, which proves that the energy is conserved better in the note.

It is fully clear that no one can make a steel pan without grooving it, but the needed amount of grooving impact is still to be revealed. My studies show that it seems to be enough to make a light groove, whose mark is barely visible in the metal of the finished pan. Presumably, this disturbs the crystal structure enough to create a sufficient acoustic impedance barrier. Future experiments with controlled mechanical grooving may reveal the effect of the groove hardness.

GROOVE WIDTH

The width of the groove presumably doesn't have any acoustical significance. But it should not be wide enough to generate any internal resonances by reflection of sound waves, i.e., the width should be less than 10-15 mm.

24. The note

The note properties that most affect the tone are the size, the shape, the tension and the arching of the note.

NOTE SIZE

The size of the note is the property that most obviously affects the tone. The size of the vibrating dent is crucial for the pitch – the larger the dent, the lower the tone. This is analogous to the situation in a guitar string or a horn, where a longer string or a longer horn results in a lower tone. But it is not as simple as in a string, because in a steel pan, notes of equal size can have different pitches, due to varying height and shape of the dent.

Another complicating ingredient in the pan is the fact that the size of the vibrating dent is not the same as the size of the note. The acoustic "size" of the note is not set by the boundaries defined by the groove, but rather by the ending of the dent arch. The size of the sounding dent is always less than the area restricted by the groove, see fig. 24.1. This is proved by the tuning, where a hit from above near the side of the note decreases the note-size and thus raises the pitch.

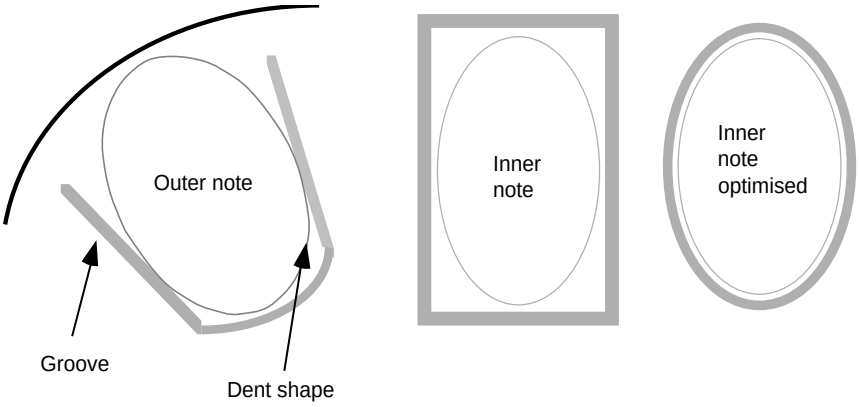

Fig. 24.1 Note dent shape in relation to groove border.

The optimal note design seems to be when the dent has the same size as the area inside the groove. In this way no space is lost. But this is a critical situation; if the note area is made too small it will be impossible get the pitch low enough. If the note is a little too big, you can always make the dent a bit smaller inside the groove. This safety-measure is the reason why the notes usually are a bit larger than they need to be. There seems to be a trend towards making the notes smaller and smaller. This is primarily done to be able to put more notes in each drum, but it may also have acoustical implications, such as minimizing the loss of acoustic energy.

I have measured the note sizes of various pans as a part of my research. It would be plausible to think that notes with the same pitch

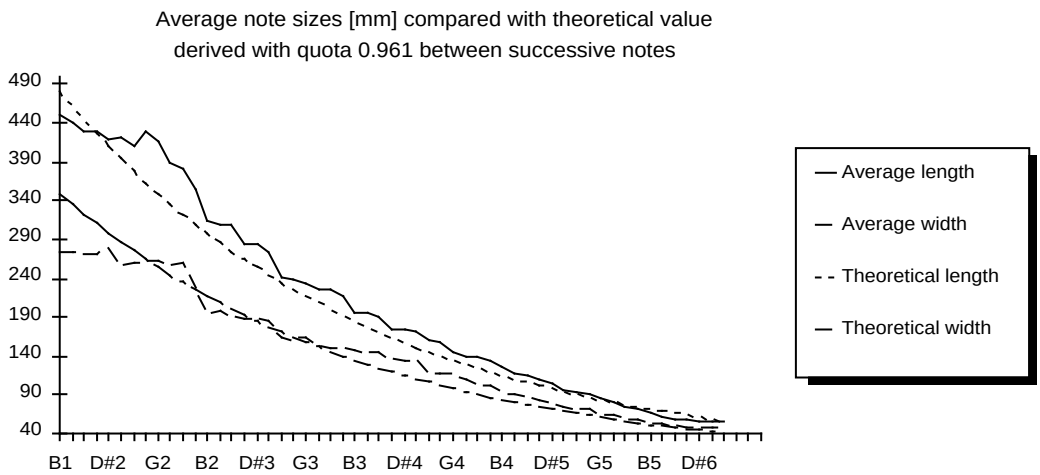

Fig. 24.2 Average note sizes.

on different pan models could have the same size. Therefore, I have compiled the data in a graph on the average length and width for each note on the musical scale, see fig. 24.2. By looking at this graph, a tuner can get a hint as to which notes of his design that can be made smaller. Please note that the lengths and widths in fig. 24.2 are measured from the groove, not on the actual note dent.

According to tuner Denzil Fernandez it is the *area* of a note that determines its pitch. He has calculated the ratio between the areas of successive notes to approximately 0.94. This means that the area of a note always is 94% of the next larger one. Converted to a ratio between lengths this will be 0.97. As a comparison, lines following this theoretical ratio have been drawn in fig. 24.2.

It would seem like an easy and straightforward project to study the relation between the note size and the pitch. But the diffuse ending of the note dent arch and the other variables affecting the pitch have made it difficult to establish a simple relationship between size and pitch. A way to progress with these studies could be to make a number of dents that exactly fill some notes with pre-defined sizes, and then try to tune them as low as possible. Such an experiment would give a practical measure of the minimum note sizes.

NOTE SHAPE

The first thing to say about the note shape is that the shape of the area delimited by the groove has little to do with the shape of the actual vibrating dent. The groove area can be of any shape, as long as the groove surrounds the dent, again see fig. 24.1. It is the shape of the dent that is important for the acoustic properties. Theoretically, the relation between the length and the width of the note should determine the frequency relationship between the fundamental, the octave and the third mode of vibration. It is still to be revealed if this is the case in practical tuning.

In old steel pans, the inner notes were often round, but nowadays they are elliptical. The upper line in fig. 24.2 represents the length of the notes and the lower line represents the width. The relationship between the width and the length is about 2 to 3 (0.65) for notes in the outer ring and about 6 to 7 (0.85) for the notes in the inner ring. This means that the smaller notes are more round in their shape, while the outer are more elliptical. Tuner Denzil Fernandez says that he is working with an average ratio that is 5 to 6 (0.83). The optimal ratio between length and width is still to be revealed.

ARCHING

The arch shape of the note dent is the most difficult property to measure, describe and relate to the tone. To a tuner, its effect on the tone is obvious, because the note needs a very special arch to generate a good steel pan tone. But how do you measure and describe an arch technically?

I started with the intention to measure the heights of various notes to see how they were related to their sizes and pitches. My first measurements revealed that the notes had one height when they were measured lengthwise and another when they were measured across. The reason for this was the lack of a well-defined plane to relate the heights to. I had related my measurements to the groove, which followed the spherical shape of the basin.

Then I started to use a shape-mould and realised that the note dents are fairly flat in their length direction, and more curved across, see fig. 24.3. I found that the quota between height and length is most often less than 1%, whereas the quota between height and width is about 2.5%, which means that a note that is 10 cm across is 2.5 mm high. The length axis seems always to be flat, regardless if the length axis of the note is oriented radially or tangentially in the pan.

The cylindrical arch is likely to be due to the cross-section between the spherical concave shape of the pan and the elliptical shape of the note. To get a better view of the arch shape, I did an experiment: I made a spherical ball of clay and then I pressed objects of various shapes against it to make indentions in it. To get a shape like an elliptical steel pan note, I had to use a cylindrical rod, see fig. 24.4.

The cylindrical arch of the dents seems to agree with the acoustical behaviour of the note. Presumably, the non-linear tone generation mechanism works best when the note is almost flat in the lengthwise direction. According to my hypothesis, the note behaves like a non-linear string in its length direction, and these vibrations generate all the high partials. If you listen to the vibrational modes across the note, you will find an acoustical behaviour that is

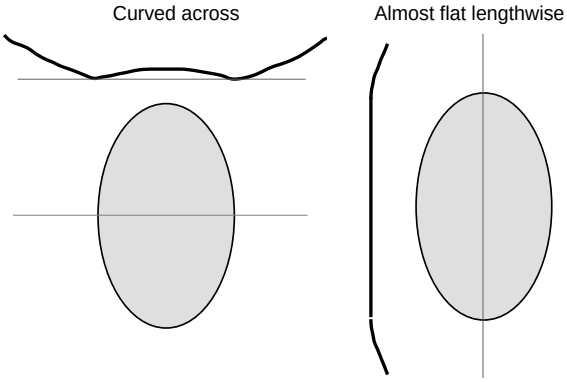

Fig. 24.3 The arch shape of a note.

much more like a shell (or a bell) with a hard and metal-like sound.

Thus, the optimal arching of a steel pan note seems to be very close to the cylindrical, raising less than one percent lengthwise. The more flat the note is lengthwise, the more partials it will generate. But a flat note will also be less stable and it will be very sensitive to strokes that tend to change its shape. Therefore, the tuning result will have to be a compromise between an ample overtone generation and considera-

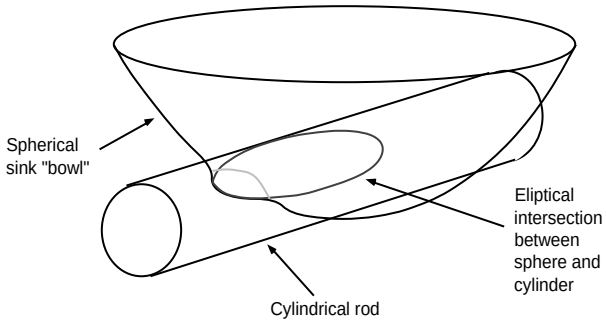

Fig. 24.4 Reproducing the cylindrical arch of a note by pressing a rod against a sphere.

tions to keep the tone stable.

There are two different tuning philosophies related to the shape and the corresponding generation of partials in the note. The first, that can be called the ”steelband” philosophy, is to shape the note with a rather high arch. Notes of this type will demand a relatively strong stroke to produce harmonic partials – to get right timbre. On the other hand, the note will be able to produce a strong sound without ”breaking”, i.e., producing a harsh, distorted sound. Due to the relative stiffness it will also stay in tune longer.

The other school of tuners, which can be called the ”jazz” or the ”soloist”, makes the notes more flat, which will make them produce a brilliant sound with many partials at relatively modest playing levels. This is good for solo or electrically amplified playing, but the flat note will produce a weaker tone and is easier played out of tune.

The best way to go further with the discussion about the shape of the arch would be to refine the measurements by using holographic methods to study the shape and the wave-patterns in the vibrating dents.

TENSION

As mentioned earlier, two notes with the same area can have quite different pitches. This is due to the arching of the note – a higher dent yields a higher pitch. This pitch change can be caused by changes in the

geometric relations of the dent but also by variations of the tension in the metal.

When a note is tuned, it is first stretched. This may result in a plastic deformation by the hammering from underneath. This stretching of the metal raises the pitch.

It is likely that the lowering during the tuning removes the stretching tension and it is substituted by a compressive tension that lowers the pitch further. This occurs because the plastic de-formation can't be compensated by a plastic "re-formation". This means that the stretched metal is not moulded together, but forced into the arch. The suppressive tension will give the note a lower pitch with the same arch height as before.

One thing that indicates the existence of suppressive tensions in steel pan notes is the notion that they tend to raise when they are played out of tune. If the only effect of playing would be that the dent was lowered by the hitting, the result would be the opposite – lowered pitches. My hypothesis here is that the playing successively releases the suppressive tension from the note, which will result in raised pitches.

It has not yet been possible to do any measurements to verify that there are any tensions in the notes of the steel pan.

TUNING

The measurements showing that the notes are cylindrical in shape and the hypothesis for non-linear partial generation give us some new clues to the secrets of steel pan tuning. There are three properties of the note that the tuner can modify while he is tuning: the size, the arch and the tension.

Variations in the area have most effect on the fundamental mode of vibration. Changes in the length affect the octave mode, whereas changing the width affects the third mode that is responsible for the timbre.

The shape of the arch is responsible for the generation of higher overtones and has to be adjusted to be sufficiently flat. The tension, last, seems to affect mainly the pitch of the fundamental.

The non-linear mechanism for tone generation shows the importance of tuning the fundamental and the octave to a perfect 1:2 frequency relationship. The secret of good tuning is to change the frequency of the fundamental and the octave separately so that they will meet at the right pitch. If the above mentioned hypothesis holds true

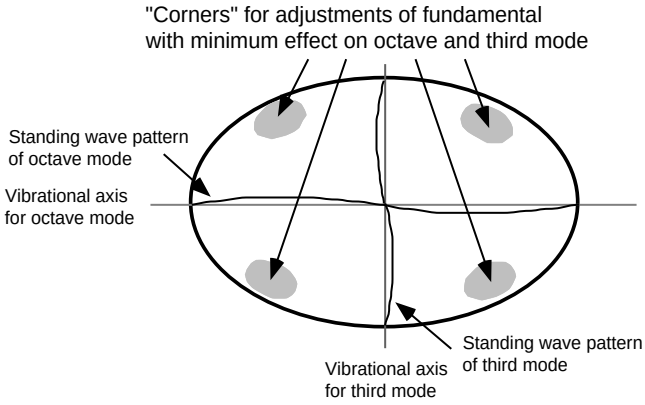

Fig. 24.5 Places to tune the fundamental with minimum effect on other modes.

and the area and the tension are mainly responsible for the frequency of the fundamental, this gives us a simplified model for the tuning: The fundamental can be changed without affecting the octave by hitting the note along the sides. This will affect the third mode, but the pitch of the third mode is not as critical as the octave.

The best place to use for changes of the fundamental, with a minimum of impact on the octave and the third mode, would be the ”corners” of the elliptical note, see fig 24.5. Lowering the note here will affect the area with a minimum of change in length and width.

The best way to adjust the octave is to re-shape the dent lengthwise – by hitting it at the ends, along the vibrational axis in fig. 24.5. These adjustments will also affect the fundamental, but to a lesser extent than the octave.

The tuning will have to be a balancing act, adjusting the area, the length, the width, the arch and the tension at the same time. The area and the tension should be adjusted so that the fundamental is right, while the length is right for the octave. At the same time, the arch shape has to be the very special one that generates harmonical overtones. The last consideration is that the width of the dent should place the third mode at a frequency that has a harmonic relationship to the fundamental.

25. Layout

The layout of the notes in the pan is, of course, important for the ergonomy of the player. But there are also important acoustical considerations in the positioning of the notes in a good pan. As the whole pan vibrates every time a note is struck, it is important that the notes that

are vibrating the most sounds well together.

To understand the theoretical foundations for a good note layout it is useful to know the musical relations of the partials of a harmonic tone, see the chapter about partials above. The intervals that have the most harmonic relationship are the octave, the fifth, the fourth and the third. If notes at these intervals ring together with the struck note, they will support its harmonic spectrum. Therefore, a favourable design is to put these notes close to each other.

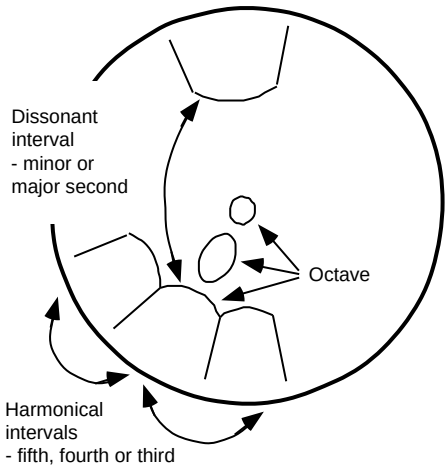

Fig. 25.1 Principle for a harmonical distribution of notes.

The general idea for a good note layout in steel pans is to position notes with a harmonic relationship as close to each other as possible, while placing notes with a non-harmonic relationship as far apart as possible. A design notion that is valid for all steel pans is that the octave counterparts always are placed close together. Fifths, fourths or thirds are also consequently placed close to each other in some pans, as in the fourths-and-fifths tenor and the quadrophonic pan with their ingenious designs.

Notes with a non-harmonic relationship – as the minor or the major second – are usually placed as far apart as possible, preferably in separate drums. If the notes with semitone intervals are spread consistently over different drums, pans with different numbers of drums will have correlated minimum intervals that have to be placed in the same drum: Two drums – a major second, three drums – a minor third, four drums – a major third.

If notes with a dissonant harmonic interval – one or two semitones apart – have to be placed in the same drum, they are usually placed on opposite sides of the drum, see the layouts of the tenor and the double second in appendix A. On the other hand, if the smallest interval between the notes that have to be placed in the same drum is harmonic, the notes are put close to each other to support each other's harmonic spectra, see the quadrophonic pan and the triple cello in appendix A.

The acoustical implications of a good layout are that it will make the pan sound better and make it easier to tune. A pan with more octave notes will be harder to tune due to the interaction of the notes. But it will also be easier to get a good tone in the end, because the notes in the upper octave will support the lower ones with higher partials. This is

very easy to demonstrate; just put a finger on a high note while playing on its lower octave counterpart – this will usually make the brilliance of the lower tone disappear.

”ROADS” BETWEEN NOTES

The acoustic function of the ”roads” – the space between the notes – is to damp the acoustic waves coming from the vibrating note before they reach the surrounding notes. This means that an increased distance (or a double groove) reduces the interaction between two adjacent notes.

The more dissonant the relation between two notes, the more they need to be separated. On the contrary, the better the acoustic separation between the notes, the less the need will be to keep the dissonant tones apart.

Sometimes, ergonomic or construction considerations are judged to be more important than the acoustical ones. The double tenor is an example of this. A double groove has been introduced to make it possible to put dissonant notes close together and still have a well-sounding instrument with many notes in it, see appendix A.

Pans that are designed with harmonically sounding notes close to each other, as the fifths-and-fourths tenor, may have adjacent notes put close together, with just a single groove between them. Octave counterparts should always be put as close together as possible, to enable positive feedback.

26. The skirt

The skirt of the pan has two major acoustic functions: First, its length determines the volume of the resonant cavity of the pan. Second, it keeps ringing after a note is struck, giving the pan a natural reverberant sound. A third possible function may be that it acts as some sort of counter-vibrator for the notes in the outer ring. Some of the notes in the outer ring lose their energy when the side is rested against a firm surface. This implies that there is an exchange of energy between the note and the side and that the side may be important for the sound radiation from the pan. The interaction between the side and the notes is still to be further examined and explained.

The length of the skirt determines how the sound produced by the notes will be coloured on its way out into the air. The sound waves emitted from the pan tend to ”creep” around to the backside of the

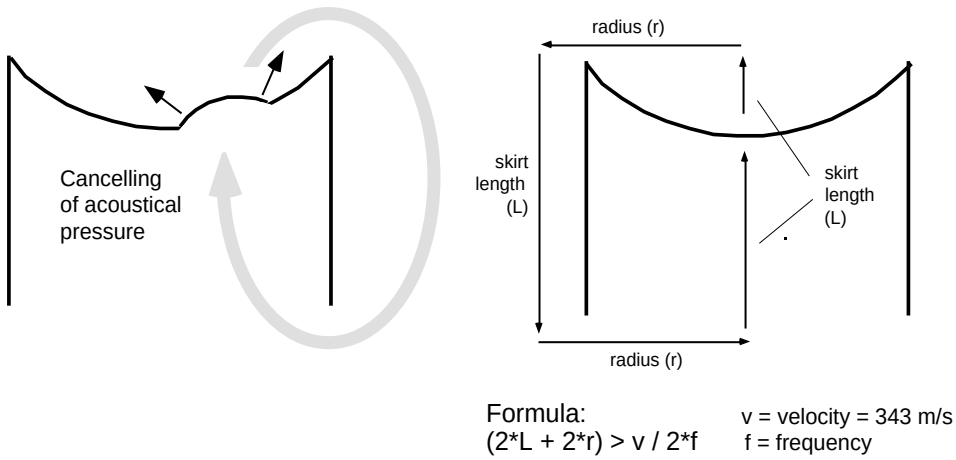

Fig. 26.1 Acoustical effect of the skirt.

playing surface and cancel the produced air pressure, see fig 26.1. If the surface of a note still is moving upwards when the sound wave reaches around, this will cancel the produced sound pressure.

This cancelling effect will be most predominant for the lower notes, as a note is vibrating slower when it is producing a low tone. If the side of the pan is made longer, it will take a longer time for the waves to reach around to the backside. This will move the cancelling effect down to lower frequencies. A physical formula for this tells us that the total length the sound has to travel should be more than the half wave-length of the sound, if no cancelling effect is to occur.

If the side of a tenor is 15 cm, the average length between the front and the backside will be about 80 cm, see fig. 26.1. This means that all notes below 277 Hz (A3) will tend to cancel and therefore be weak in sound. Fortunately, this is below the range of the tenor (lowest note D4).

But what if we were to design a cello pan that goes down to B2 (123 Hz)? The formula tells us that the side would have to be at least 40 cm. The side of a regular cello is about 45 cm, so this is in accordance with the theory. What about a six bass with lowest note B1 (62 Hz)? This gives a side of minimum 100 cm, which is about 10 cm more than the length of the standard steel drum. This indicates that basses may be improved by lengthening the side.

As the resonant effect of the skirt doesn't affect the pitches of the notes, it is possible to make pans of the same model with very different side lengths. The length is chosen according to the desired sound "colour" of the pan, see appendix A. The lower the pitch, the longer the side.

The reverberation effect of the side will be more prevalent the longer the side is. The reverberation will also tend to have a pitch of its own. A long side will have a low pitch and a shorter side will have a higher pitch. But the pitch of the skirt is so low that it will not interact with the notes, just ”colour” the sound with a constant low tone, resulting in the typical steel pan timbre.

27. Sticks

Last in this discussion of the theoretical implications of the various parts of the pan, we have to take a look at the sticks. While the sticks are not a physical part of the instrument, they still play a very important role in the tone generation.

To get a sound out of a musical instrument you have to get it to vibrate in some way – to put energy into it. This is called the *exitation* of the note, and the properties of the exiting body are of vital importance for the tone. The properties of the stick that may have importance for the tone are: weight, length and hardness.

WEIGHT AND LENGTH

The importance of the weight of the stick is easy to understand. The heavier the stick, the more energy can be transferred to a note when it is hit. This means that a heavier stick gives the pan a stronger tone, but on the other hand you risk getting a sound that ”breaks”. It is also easier to hit the notes out of tune. The same thing goes for the length – a longer stick makes louder playing possible. The acoustical implications of the weight and the length as such can almost be disregarded, as they can be seen as a part of the stroke, the force of which the player can vary within a wide range.

HARDNESS

To get a good sound out of a pan it is important to have sticks with the right hardness. If the sticks are too hard, the sound will be harsh with a weak fundamental and many non-harmonic overtones. If they are too soft the tone will be weak and muffled. Small notes need a hard stick and big notes need a soft stick to sound good. This means that ideally you should use sticks with varying hardness for the different sized notes in one pan. This is not possible, of course, so you have to compromise.

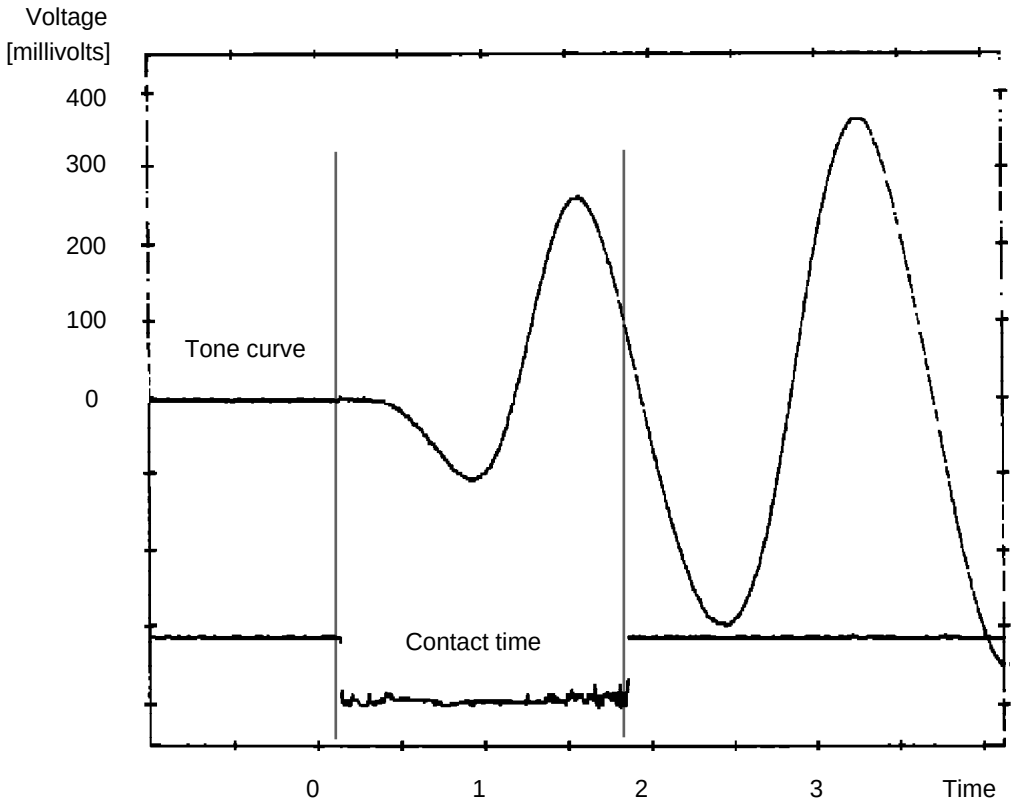

Fig. 27.1 Contact time of the stick in relation to the first milliseconds of a steel pan tone.

of the striking indicate that the optimal hardness of the stick seems to be when the contact time equals the period time of the fundamental, see fig. 27.1. This results in the fundamental being the only vibrant mode of the note that is exited by the stroke. The higher modes, that vibrate faster than the fundamental, will tend to move up and down several times during the time of contact, which causes them to be damped by the soft stick.

The smoothness of the beginning of the curve in fig. 27.1 also shows that it is only the fundamental that vibrates in the beginning of the tone. The ruggedness occurring later shows that the higher partials are beginning to occur, see fig. 19.1.

The findings on the exitation of the note are well in line with my hypothesis concerning the sound generation. According to this, the exitation that would lead to the most harmonic tone would be a stroke that only excites the fundamental mode of vibration, and lets the non-linear mechanism do the work of converting the energy to the higher, harmonic partials.