Dept of Speech, Music and Hearing

ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Erik Jansson

Fourth edition2002
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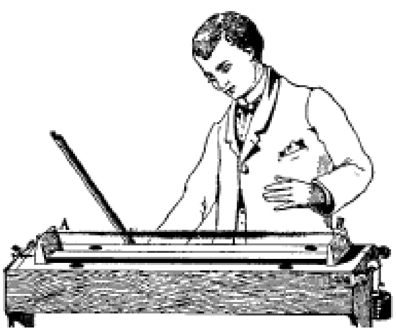

Index of chapters

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PREFACE

The aim of this compendium is to build an understanding for the acoustics of the guitar and the violin, and to explain how their different parts cooperate. This will be done with results obtained by research. I shall show what can be measured and what can be perceived by our ears. Further I shall hint at measuring procedures that the maker himself may develop. Finally I shall show how "standard" laboratory equipment can be used to measure characteristics of the violin and the guitar, which partly shall be used by the participants of this course. Much energy has been devoted to balance an informative presentation without too much complication. Hopefully this balance is appropriate for many readers.

The material presented is a combination of well known acoustical facts, late research on the acoustics of the violin and the guitar and results of the latest results of the ongoing research at KTH. The material has been collected by some 30 years of research and co-operation with a large number of persons and institutions. At my KTH-home, the Department of Speech, Music and Hearing, Prof. Johan Sundberg, Dr Anders Askenfelt, our first Dr of Music Acoustics Jesus Alonso, Prof. Gunnar Fant and his successor Prof. Björn Granström, all friends and colleagues have helped and inspired my work, and especially Mrs. Gudrun Weiner-Rispe who has plotted a large number of the figures. Much material has been collected at the Department of Physics II, KTH and the Institute of Optical Research headed by Profs Erik Ingelstam and Klaus Biedermann together with my optical "colleagues" Drs Nils-Erik Molin and Leif Ek. Of the many makers I early came into contact with are Harry Sundin and Gunnar Mattson of the Stockholm Violin Maker's Club. Much work has been made in co-operation with Göran Levvin at AB Herman Carlsson Levin and Carlo and Birgit Hansen at Carlo Hansen Violinateljé AB. Lately much work has been made together with the Division of Experimental Mechanics at Luleå University of Technology and my early colleague Prof. Nils-Erik Molin, Prof. Lars Frydén and Benedykt Niewczyk, violin maker from Poznan Poland. Without all this help and co-operation, this information would never have been collected and summarised. In addition I would like to add two names: Prof. Arthur Benade and Dr Carleen Hutchins, who both have taught and inspired me a lot. Although much material is presented mainly from work by the author, it must be pointed out that there is much more collected by other persons. The manuscript has been read by Dr. Rodney Day which has resulted in considerable improvements, both presentation and language. I want to thank these persons and all other helpful persons not named. Misinterpretations and negligence to present important material by others is the fault of the author, who asks for forgiveness for his misbiased judgement.

The course is limited to acoustical fundamentals for the violin and the guitar. It is presented with little or no mathematics. Additional valuable information can be found in the CAS Journal (earlier called Newsletter). For readers with a more general interest in musical acoustics I recommend "The Science of Musical Sounds" by Johan Sundberg (Academic Press, Inc. 1991), which should be a good supplement to this course. Much information is collected by Dr Hutchins in Benchmark Papers in Acoustics (Dowden, Hutchinson & Ross, Stroudsburg, Pennsylvania, vol. 5 1975, vol. 6 1976) and Research Papers in Violin Acoustics 1975-1993 (Acoustical Society of America through American Institute of Physics, 1996). The financial supports by above institutions, the Swedish Humanistic Science Research Council, Swedish Natural Research Council, Swedish Board for Technical Development, Carl Trygger Scientific Foundation, Wenner-Gren Scientific Foundation, and Swedish Institute are gratefully acknowledged.

Stockholm 2002- Erik Jansson

The present compendium has been used teaching acoustics for violin and guitar makers by the author. The material contains in parts original information not generally known and therefore it has been translated into English and made public on the Internet. The written information can, however, be difficult to read for many makers. If questions, they can be directed to the author, erik@speech.kth.se, who hopefully can answer them. A simplified version may be put together after retirement, i.e. after 5 years if judged to be interesting.

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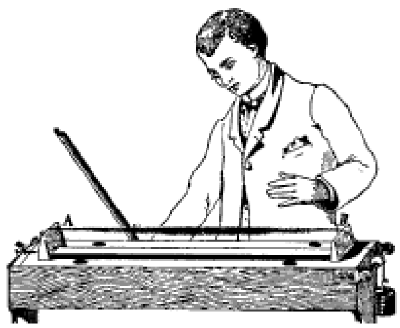
Dept of Speech, Music and Hearing

ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Erik Jansson

Chapter I:
Sound and Hearing

Fourth edition 2002



ACOUSTICS FOR VIOLIN AND GUITAR MAKERS

Chapter 1 – Fundamentals of acoustics
SOUND AND HEARING

Chapter 1.
FUNDAMENTALS OF ACOUSTICS - SOUND AND HEARING
First part: THE SOUND

INTRODUCTION

In this first part of chapter 1 properties of sound will be presented. Fundamental measures such as frequency and level will be introduced. The measures will be developed into spectrum and time histories (oscillograms). Sounds as musical tones, single tones and noise will be described by their spectrum representation and by their time history representation.

1.1. WHAT IS SOUND?

Sound is quick and microscopically small variations in the barometric air pressure. The variations are described by two fundamental acoustical measures FREQUENCY and LEVEL. FREQUENCY is related to the pitch, i.e., a low frequency corresponds to a low pitch and a high frequency to a high pitch. LEVEL relates to loudness, i.e. a low level corresponds to a weak sound and a high level to a loud sound.

A simple example can illustrate that air pressure variations are sound, see Fig. 1.1. A loudspeaker emits sound. A loudspeaker placed with its opening directed upwards emits sound upward through the opening. A sheet of paper placed over the loudspeaker opening will vibrate and give a rattling sound. The loudspeaker membrane moves up and down, which will result in the following interaction with the paper sheet:

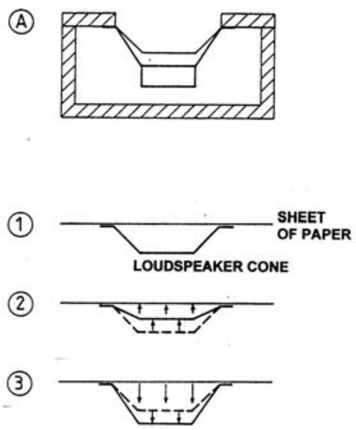


Figure 1.1. Cross-section of a loudspeaker box seen from the side, and stages 1 to 3 described in the text. The arrows mark the position of the loudspeaker membrane in relation to its equilibrium and the varying air pressure (the sound pressure) acting on the paper sheet, respectively.

1. At the equilibrium position of the loudspeaker membrane the air pressure is the same below as above the paper and the paper sheet is not moving.

2. When the loudspeaker membrane moves upwards, the air is compressed under the paper and the increased air pressure pushes the paper upwards.

3. When the membrane moves towards its lowest position the air pressure is lowered and the paper is pulled down towards the loudspeaker.

The experiment is easily made and it shows that the vibrations of the paper sheet (a rattling sound and sensations of tickling in a hand held over the loudspeaker) are related to sound. When the loudspeaker emits strong sound the paper rattles strongly (strong hand tickling), and when the loudspeaker emits weak sound the paper rattles weakly (weak hand ticking).

HOW LOUD IS THE SOUND – LEVEL?

The strength of the sound, the sound pressure level is measured in dB (decibel soundpressure level – mathematically the level relative to a sound pressure of 0.00002 Pa). To give a coarse feeling for sound pressure levels three extreme examples are given in Table 1.1 and to give a more detailed feeling, some sound pressure levels typically met in daily life are given in Table 1.2. The barometric sound pressure, well above the threshold of pain, can only be obtained theoretically (mathematically).

Table 1.1. Sound pressure levels – minimum to maximum and barometric pressure

Faintest audible sound	0 dB
Loudest (without pain)	120 dB
Barometric pressure (760 mm Hg)	194 dB

Table 1.2. Sound pressure levels of typical sounds

Threshold of pain	120 dB
Disco	100 dB
Heavy traffic	80 dB
Conversation	60 dB
Library	40 dB
Rustling of leaves	20 dB
Threshold of hearing	0 dB

PITCH OF THE SOUND - OR FREQUENCY?

Frequency is a measure of how often an event (in the time history) is repeated per second and the unit of measurement is Hz (hertz). Often the given frequency unit is kHz (kilohertz), which is 1000 Hz in the same way as 1000 gram is 1 kilogram. Thus 2 kHz and 2 000 Hz are the same.

Example 1.1. A metronome adjusted to 60 gives 60 beats per minute, which equals 1 per second and the frequency is 1 Hz. If the metronome is readjusted to 120 it gives 120 beats per minute, which equals 2 per second and the frequency is 2 Hz.

Example 1.2. Sound is the vibration of air. If the membrane of a loudspeaker moves out and in 20 times a second, i.e., with the frequency 20 Hz, we can hear a very low tone. If the membrane moves in and out 440 times per second, we hear a tone of 440 Hz, i.e. the standard tuning A (A4).

The young, fresh human ear can hear sound approximately from 20 to 20 000 Hz, i.e., from 0.02 to 20 kHz. The frequency of the lowest note on the piano has a frequency of 27.5 Hz (A0 nominal value) and its highest note is 4.186 kHz (C8 nominal value).

1.2. SOUND AND SPECTRUM

Let us look at pictures of the sounds. What do the sounds "look like"? Usually one draws the spectrogram of a musical note, shortly to be called the SPECTRUM. The spectrum is an acoustical snapshot of the note. The spectrum can be explained by means of Fig. 1.2.

The horizontal scale - the frequency axis - of the spectrogram corresponds to the staves in the musical representation. A specific tone has a specific staff such as the note A of 220 Hz. In the spectrogram the tone is represented by a bar (a vertical line) at the frequency 220 Hz. The strength of the tone, strong (musical ff) corresponds to a high bar and weak (musical pp) corresponds to a low bar. The level of the tone can be read at the (vertical) level scale in dB and its frequency at the (horizontal) frequency scale in Hz. It has thus been shown that the frequency in Hz and level in dB can describe a TONE. The TONE is an acoustical building stone of the sound we hear.

Example 1.3.a) The time signal (at least in Sweden) contains a tone of the frequency 1000 Hz, i.e., 1 kHz. The level of the tone can be adjusted by the volume control.

b) The tuning forks with the standard tone give a tone with the frequency 440 Hz. The level is high in the beginning and decreases slowly. A stronger hit gives a higher level.

Most musical tones do not have the simple representation shown so far. They consist of several tones, c.f. Fig. 1.3. The musical tone A 220 Hz in Fig. 1.3 is placed two staves below the five permanent ones (in guitar notation 110 Hz, a transposition to one octave lower). A more complete representation has been given on the staves to the left, i.e. a tone (the fundamental), a tone an octave higher (acoustically twice as high), a tone an octave plus a fifth higher (three times as high), a tone a double octave higher (four times as high), and a tone a double octave plus major third higher (five times as high). The played notes of the melody instruments such as violin, clarinet and trumpet are made up by several single tones as sketched in Fig 1.3.

The spectrogram of a real musical tone consists of several bars, c.f. Fig. 1.3. The frequencies of the bars can be read at the horizontal scale. The levels of the different tones, the heights of the bars, can be read at the vertical scale. The different tones are called PARTIALS (harmonics) and the lowest partial is called the FUNDAMENTAL. A little closer look reveals that the frequency of the second tone is twice that of the fundamental, the frequency of the third partial is three times that of the fundamental, etc. The bars show the SPECTRUM of the musical tone. The partials are numbered 1, 2, 3 etc. and the partial frequencies are 2,3 etc times that of the fundamental. The frequency of the fundamental corresponds to the pitch and the levels of the partials correspond to the timbre. The spectrum of a sound is measured with a spectroscope.

The spectrogram of the musical tone in Fig 1.3 show five partials (bars), which are placed at even distances. The partials are equally strong, i.e. of the same level, as the five bars have equal height.

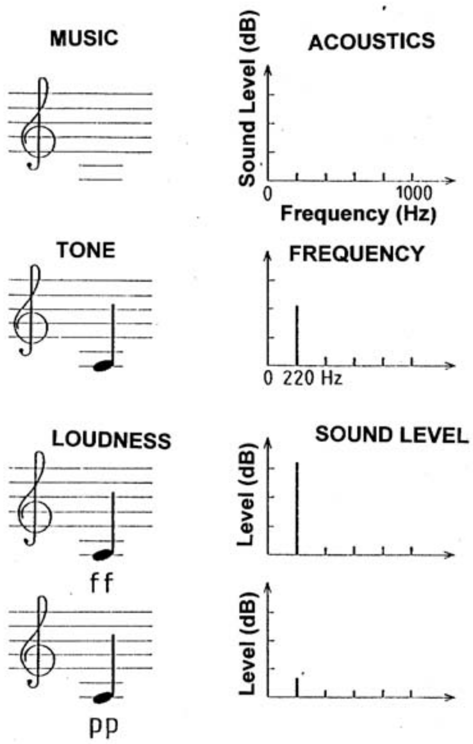


Figure 1.2. Musical description and acoustical description of a tone.

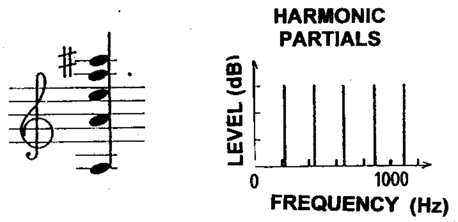


Figure 1.3. Musical description of a real tone and acoustical description.

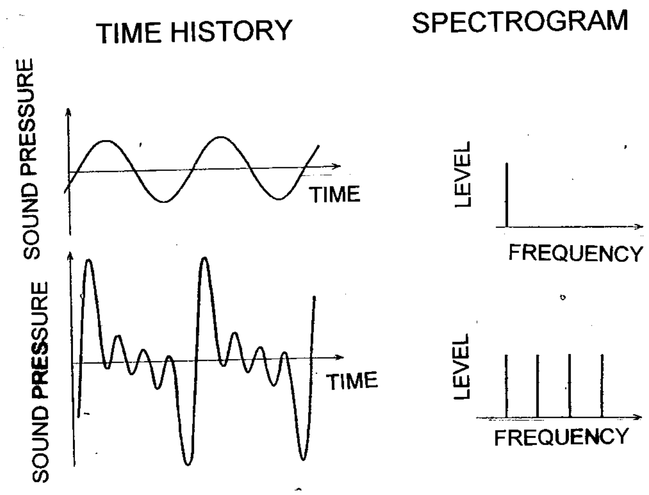


Figure 1.4. Time histories (left) and spectra (right) for a) a simple tone (upper plots), and b) a more real tone (lower plots) with four equally strong partials.

Example 1.4. A violinist plays the open A-string, i.e., a spectrum with the fundamental of 440 Hz. The second partial has the frequency 2 times the fundamental, i.e., 2 times 440 equals 880 Hz. In the same way the third, fourth and fifth partial frequencies can be calculated as 3, 4, and 5 times the fundamental frequency, respectively. The frequencies are 1320 Hz (1.32 kHz), 1760 Hz (1.76 kHz), and 2 200 Hz (2.2 kHz), respectively.

1.3. TIME HISTORY OF THE SOUND

The simple tone with only one partial (= the fundamental) has a time history (oscillogram) and a spectrum corresponding to Fig. 1.4a. The time history repeats itself after equal time intervals. A spectrum with four equally strong partials has a time history corresponding to Fig. 1.4b (the simplest case). The time history repeats itself after equal time intervals here too. The time history is considerably more complicated though than that of one partial.

A played tone does not look the same all the time. It may look as in Fig. 1.5. This played tone has a beginning, an extended constant (more or less) part and an end. The beginning is usually called the starting transient and corresponds musically to the attack. The end of the tone is usually called the ending transient and corresponds to the decay of the string vibrations. The time history is measured with an oscilloscope.

Example 1.5. The motion of the tuning fork is very rapid but the tone of a tuning fork decays slowly, c.f. Fig. 1.6. It vibrates so rapidly but decays so slowly that it is not possible to plot in detail the sound pressure variations and the full ending transient. In the upper part of Fig. 1.6 the time history of the decaying motion has been drawn. Below, parts of the time history has been enlarged considerably, i.e., the central part shows the detailed time history at three instants. In the lower part of Fig. 1.6 the spectra corresponding to the three instants have been plotted. The figure shows that the tuning fork gives a simple tone at the different instants and a single partial bar in the spectrum (c.f., Fig. 1.4a). The sound pressure decreases slowly and thus the level of the single partial decreases slowly.

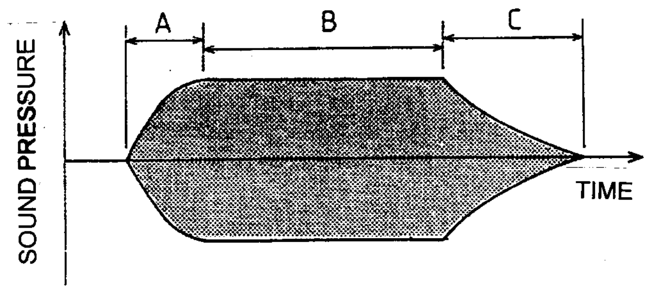


Figure 1.5. Time history of a tone in principle: A the starting transient, B the constant (more or less) part, and C the ending transient (the oscillations are generally to close to be drawn, and are marked here by the shade).

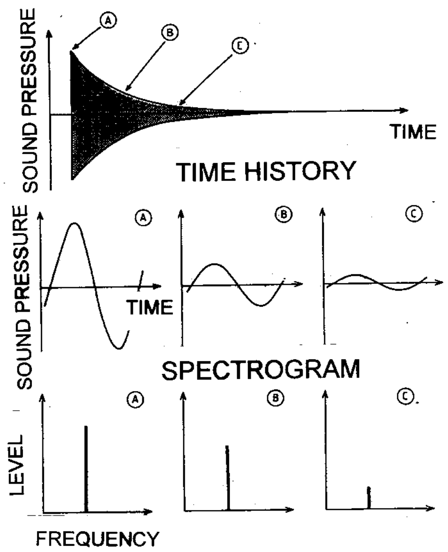


Figure 1.6. The full time history of the tone of a tuning forks (an ending transient), detailed time histories and corresponding spectra.

Example 1.6. The pipe organ is an instrument, in which the starting transient is most important. It can be adjusted differently and can give different sounding qualities. Two different starting transients of the same pipe are shown in Fig. 1.7. The upper time history is somewhat more complex than the lower one. In a detailed time history one can read that the second partial (the octave shown as the fine pattern shade) dominates during the earliest part (0.02 to 0.03 seconds): Thereafter the first partial (the fundamental, the coarse pattern shade) starts to dominate. In the lower time history the first partial dominates the starting transient and just increases.

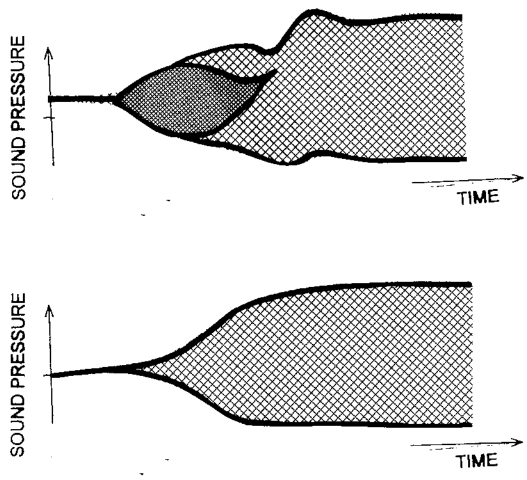


Figure 1.7. Time histories (shaded oscillograms) of starting transients of two pipe organ tones, the same pipe differently adjusted. In the upper frame the second partial dominates initially (dark area) the time history, in the lower frame the fundamental (the lowest partial) just grows (after Sundberg 1966).

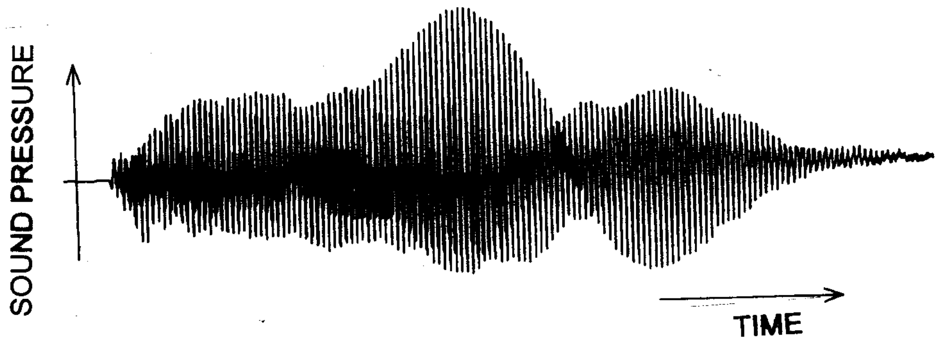


Figure 1.8. Time history (oscillogram) of a played violin tone.

Usually technical people measure time in units of 0.001 seconds, which are called ms (milliseconds) compare m (meter) and mm (millimetres), 1 mm being 0.001 m).

Example 1.7. A musical instrument such as the violin results in still more complicated time histories, c.f., Fig. 1.8. The time history is changing all the time in a specific way and monitored by the skilled musician. If one listens to the early, the middle, and the late part of the tone (by computer manipulations this can be done) one will hear that the loudness, timbre and also the pitch of the tone are different in the different parts. Timbre and pitch will be defined later in this chapter

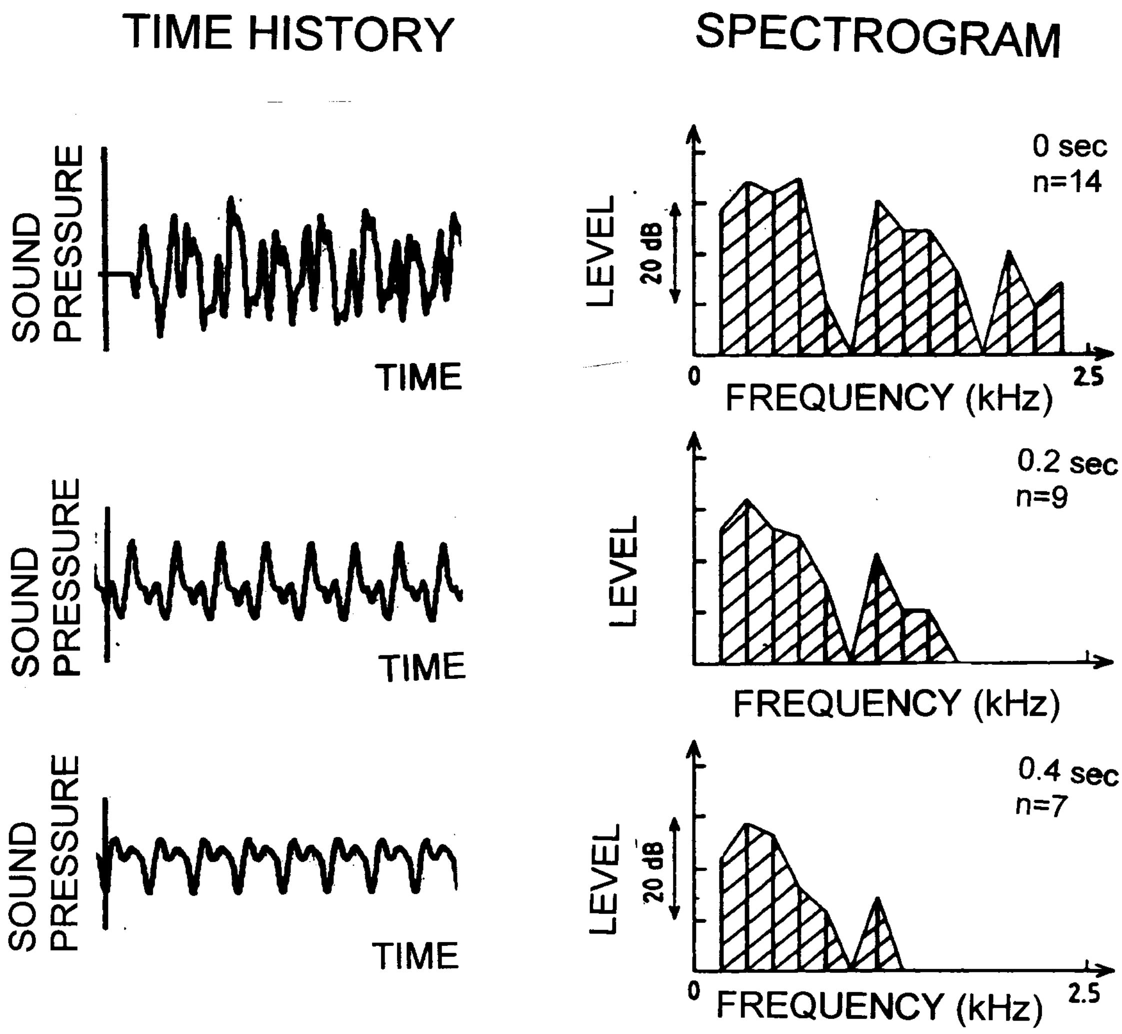


Figure 1.9. Time history (left plots) and spectra (right plots) of a guitar tone immediately after attack, 0.2, and 0.4 seconds later.

Example 1.8. The guitar string is plucked and is thereafter left to decay freely. The time history of a guitar tone may look as in Fig. 1.9. It is rather irregular at the attack, but shows clearly repetitive (periodic) time histories at the later two instants. The time histories are more similar to that of Fig. 1.4 b (four partials) than that of Fig. 1.4a (one partial only). The spectra corresponding to the different instants also show that the guitar tone is made up by several partials. It shows 14 partials just after the attack, 9 after 0.2 seconds, and 7 after 0.4 seconds. The levels of the partials decrease differently. The highfrequency partials decay faster than the lowfrequency ones. Every partial can be thought of as produced by a tuning fork and the tuning forks of the different partials decay with different speeds. The shown guitar tone could be produced by fourteen different tuning forks and not by one (the line between the partial peaks is called the spectrum envelope).

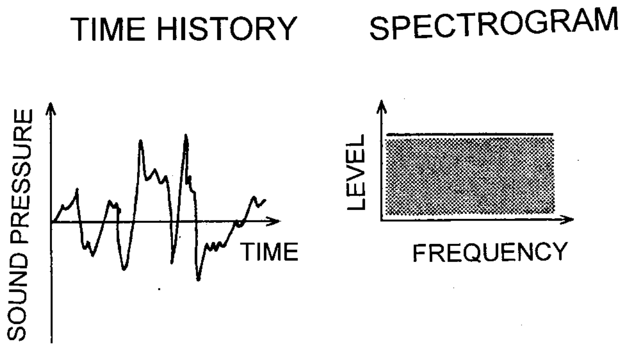


Figure 1.10. Time history (left) and spectrum (right) of noise.

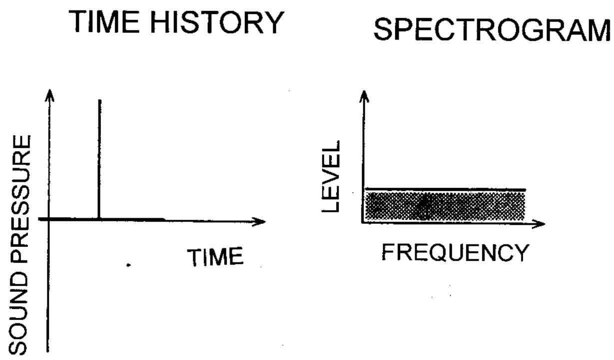


Figure 1.11. Time history and spectrum of an impulse.

NOISE AND IMPULSE SOUND

In the violin-making world and in modern technology two different kinds of test sounds are used, i.e. IMPULSE sound and NOISE sound.

NOISE is technically a sound that has irregular variations with time. Noise has the property that it contains partials at all frequencies and on average of the same level.

A noise thus contains partials at 100 Hz, 101 Hz, 102 Hz, etc. It has also partials between 100 Hz and 101 Hz, i.e. at 100.1 Hz, 100,2 Hz .... 100.8 Hz, and 100.9 Hz. But between these partials there are also partials at 100,11 Hz, 100.12 Hz, etc. Between the latest partials there are also partials and so on. The noise is made up by a spectrum of infinitely densely packed partials, which on average are of equal strength (technically called white noise). At any frequency there is a partial, for instance at 100 Hz and 173.937 Hz.

The time history for a noise sound may look as in Figure 1.10 , a completely irregular and wriggly curve. The spectrum looks as in the right part of the figure. The partials are so densely packed that single partials can not be seen and all partials are on the average equally strong.

Example 1.9. a) A television set emits noise when the transmission is turned off after the end of the last program.
b) When a wooden surface is ground with sandpaper noise is obtained.

An impulse is a single short sound (a spike) with a time history as shown in Fig. 1.10b. The impulse has partials of all frequencies (as the noise) but only at one instant.

Example 1.10. a) When you hit a nail with a hammer, an impulse is obtained at the moment of the hammer impact.
b) When you hit a violin top plate with you knuckle, an impulse is obtained at the moment of impact.

Violinmakers use these two kinds of sounds to test the properties of a free top plate for instance. By letting a finger slide along the top plate surface a noise sound is obtained. Depending on the acoustical properties of the plate some partials of the noise are amplified. The maker can hear a sound of certain pitch and timbre. With some experimenting the maker can learn to use the procedure as a guiding test during the shaping process.

The violinmaker can also use impulsive sound. By tapping (knocking) the free top plate with a knuckle, an impulsive sound is injected (the procedure is the same as hitting the tuning fork at a table edge). The response of the plate to the injected impulse give the resonances of the plate (each corresponding to a tuning fork giving different pitch, level and time decay). Thereby the pitches, levels and decays of the resonance vibrations reflect the properties of the plate and can guide the maker towards a wanted result. The maker cans optimise the tapping sound for specific purposes. By hitting with a soft "club" (the fingertip) the low resonances vibrations are favoured (longer duration of the impulse). The impulse spectrum is also changed. A softer club gives a spectrum with weaker partials at high frequencies.

In tones from musical instruments there are also impulsive and noisy sounds, which can be important for the timbre.

Example 1.11. a) When the violin bow is pulled over the string, a musical tone is generated, which also contains noise.
b) Noise can be heard in the beginning of the irregular time history of the guitar tone, c.f., Fig. 1.9. When a left hand finger slides along a wrapped string, noise is generated.
c) In wood wind instruments such as the clarinet, air turbulence causes noise in the same way as for a microphone outdoors in wind. Hitting a key gives impulsive sound.

1.4 SUMMARY: THE SOUND

In this part I have shown what a played musical tone can look like. It consists of very small and rapid variations in the atmospheric pressure. The variations are as a rule complicated. The time history of the tone varies with timbre. In addition the played tones have a beginning and an end, i.e. a starting transient and an ending transient. The spectrum of a tone shows an instantaneous view of the tone at one particular time. The spectrum varies from one part to another of the same tone. As a rule a spectrum representation is not typical for all tones of the played instrument.

1.5 KEY WORDS:

Frequency, Hz, kHz, level, dB, spectrum, partials, fundamental, time history, ms, starting transients, ending transients, noise, and impulse.

Chapter 1.
Second part: THE HEARING PROCESS

INTRODUCTION
In the second part of the first chapter the measured properties of sound will be connected to the perception by our hearing. First the function of our hearing organ is sketched, the sensitivity and the working range. Thereafter masking phenomena and the so-called critical bands of hearing are introduced. Finally timbre and spectrum of tones are discussed.

1.6. THE EAR AND THE HEARING PROCESS

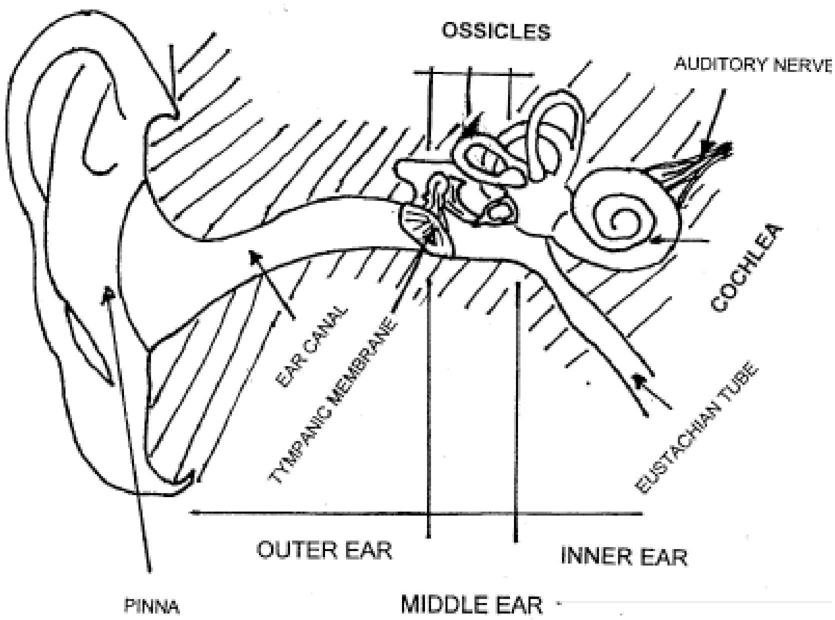


Fig 1.12. Sketch of the ear.

The ear is a very complicated microphone with a built-in spectroscope, c.f., Fig. 1.12. The outer part of the ear or the pinna is the part we in everyday language call the ear. The pinna works as an antenna, picks up the sound, leads it via the auditory canal to the eardrum or tympanic membrane (corresponding to the microphone membrane). The vibrations of the eardrum are coupled via three small bones, the ossicles, to the oval window of the cochlea, c.f. Fig. 1.13a. The vibrations of the oval window set the upper liquid filled part of the cochlea, scala vestibuli, vibrating. The vibrations of the liquid will in its turn make the basilar membrane vibrate.

Muscles connected to the ossicles adjust the sensitivity of hearing, i.e. these work as an automatic volume control. By adjusting the sensitivity, the hearing is protected against strong sounds. The sensitivity adjustment takes, however, a short time during which the hearing is "unprotected". Therefore this adjustment can not protect our hearing against strong impulsive sounds, such as the firing of a gun. For very high sound levels it is also insufficient and ear protectors must be used.

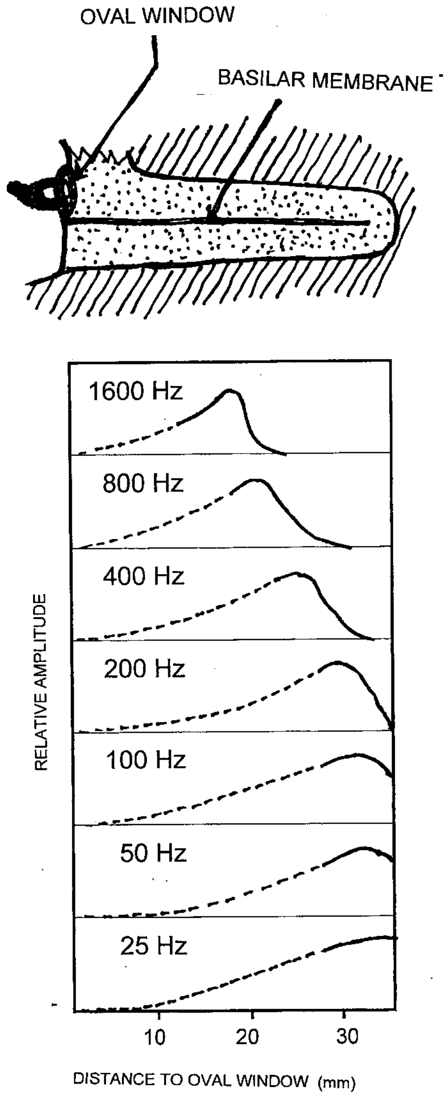


Figure 1.13. a) Sketch of the function of the outer ear (upmost picture). The cochlea has the shape of a spiral with 2 and 3/4 turns, but has been drawn straight to give a clearer picture (after Hadding and Petersson). b) The displacement of the basilar membrane at different frequencies (frames below picture, after Denes and Pinson).

The basilar membrane is the part where the mechanical vibrations are transformed into electrical nerve pulses, see Fig. 1.13a. For single tones the basilar membrane gives maximum

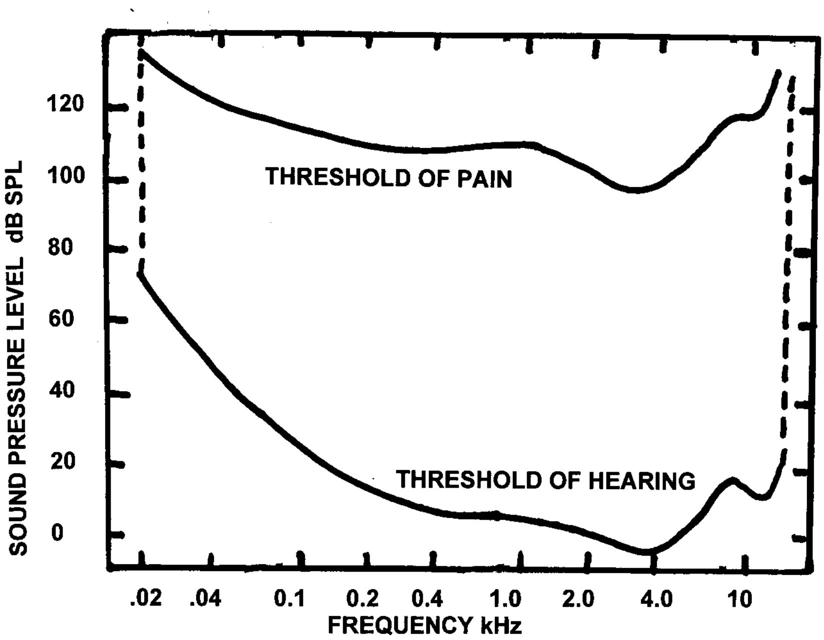


Figure 1.14. The working range of the hearing

vibrations at special positions depending on their frequencies. Low-frequency tones give a maximum far away from the oval window and high frequency tones close to the oval window see Fig. 1.13b. At the basilar membrane there are vibration sensitive cells, so called hair cells. It is the hair cells that react to the basil vibrations and transmit the nerve pulses. If we put our hand close to a loudspeaker we feel tickles, which are registered by the brain. If we put a part of our arm close to a loudspeaker it is received by the brain as tickling at a specific position of the arm. In a similar way the brain registers the positions of the basilar membrane vibrations. Different frequencies correspond to different places, which makes the basilar membrane act as a spectroscope.

THE HEARING PROCESS

The ear works as a complicated microphone as has been shown. The working range of hearing covers frequencies from 16 to 16 000 Hz (16 kHz), c.f., Fig. 1.14. This is a wide frequency range corresponding to 10 octaves (visible light has a much, much wider frequency range, from 390 000 000 000 000 to 750 000 000 000 000 Hz but this is less than a one-octave range in musical language). The dynamical working range of hearing is from -5 to 120 dB. The lower limit where a tone is just noticeable is called the HEARING THRESHOLD. The hearing threshold is different for different frequencies and is at the lowest at -5 dB at 2 kHz. The upper limit is called the PAIN THRESHOLD, because here the hearing sensation is changed into a sensation of pain (if a sound results in a pain sensation, stick a finger in each ear and leave the sounding area immediately). The threshold of pain is approximately at 120 dB. The maximal working range of level from -5 to +120 dB, i.e. close to 120 dB. A digital tape recorder is needed to cover this range. The hearing threshold varies appreciably with frequency. At 30 Hz the hearing threshold is at 60 dB. Between 500 Hz and 5 000 Hz it is approximately at 0 dB. For frequencies above 5 000 Hz the hearing threshold increases rapidly. The threshold of pain can be regarded as independent of frequency and constant at 120 dB.

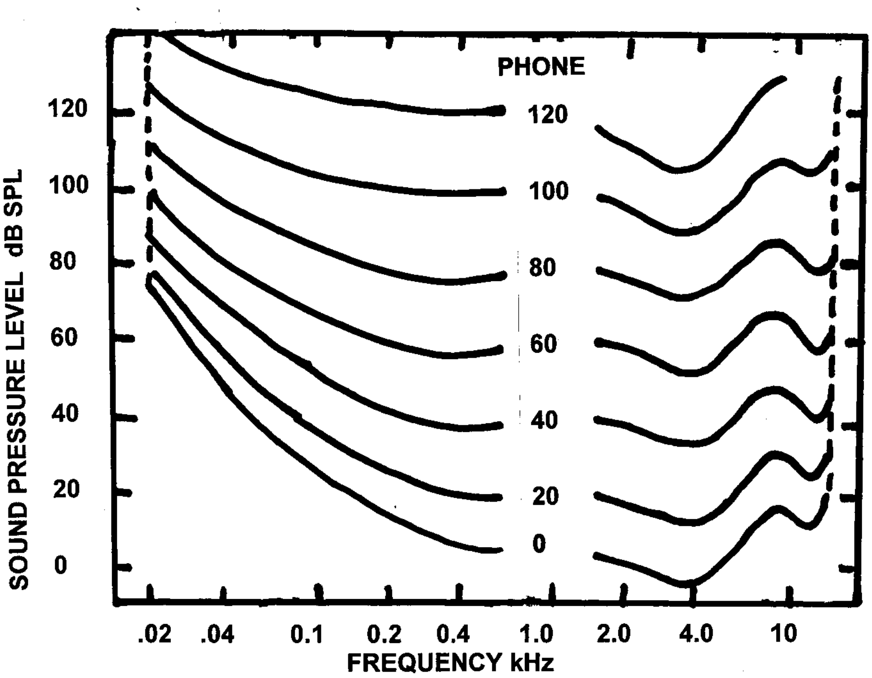
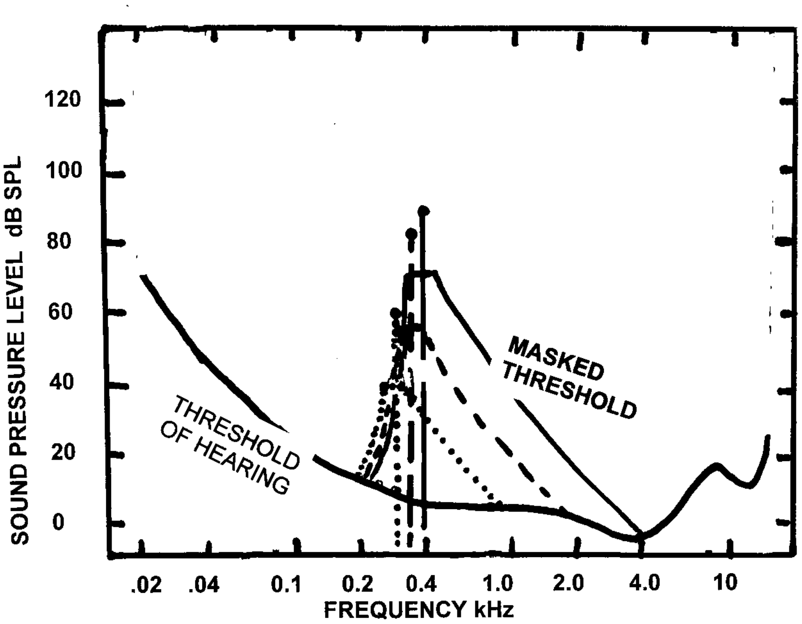


Figure 1.15. Levels of equal loudness (phone-curves)

The loudness of a tone depends both on its frequency and its level. Fig. 1.15 shows the level that a tone should have to give the same loudness at different frequencies. Levels of equal loudness have been plotted starting from 0, 20, 40 etc. dB at 1 000 Hz. The figure shows, that for frequencies below 500 Hz a fairly loud sound is necessary to be heard (the hearing threshold is at a fairly high level). Above the hearing threshold the lines of equal loudness are closely spaced, i.e. our hearing is very sensitive to increased sound level at low frequencies. The hearing threshold and the sensitivity decreases up to 500 Hz. Between 500 Hz and 5 000 Hz the equal loudness lines are approximately horizontal and parallel, i.e. the hearing is equally sensitive in this range and corresponds to the volume control of an amplifier.

The importance of the equal loudness lines can be evaluated in a different way. At low sound levels the sensitivity of hearing is rather different at different frequency ranges, especially at low frequencies. At higher sound levels these differences become less prominent, the equal loudness lines become more horizontal. Thus the hearing properties can be summarised in the following way. Different sound levels give different sound impressions. High sound levels favour the low frequency sounds (the bass sounds).



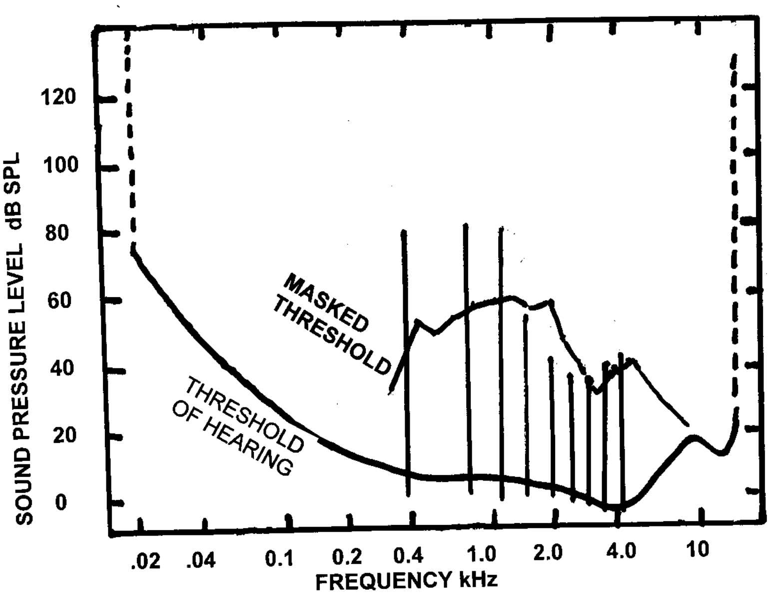


Figure 1.16. Masked threshold of hearing from a) a simple tone of constant frequency but varying level and b) from a tone spectrum (from Sundberg)

1.7. MASKING CRITICAL BANDS AND ROUGHNESS

Different frequencies give different positions of maximum deflections of the basilar membrane (cf., Fig. 1.13b). This fact explains two fundamental hearing phenomena, MASKING and ROUGHNESS.

The masking effect is that a sound may hide or mask, another, weaker sound. In the presence of a tone the hearing threshold (for an additional tone) is partially increased from the hearing threshold (in silence, the hearing threshold of one tone only). This so-called masked hearing threshold is 10 dB below the level of the first tone for another tone close in frequency. For frequencies below the masking tone, the hearing threshold soon reaches the threshold of hearing in silence, c.f., Fig. 1.16a.

For frequencies above that of the first tone, the masked threshold is considerably higher than the hearing threshold in silence. For a tone as marked with a bar at 0.4 kHz (400 Hz) it is easily seen that the masked threshold (the full line leaning downwards to the right) lies considerably above the silence threshold up to 4 kHz. Towards lower frequencies the masked threshold is only higher to 0.2 kHz (200 Hz). The condition for a second tone to be noticed is that its level is above the masked threshold (it is not sufficient that its level is above the threshold in silence). The rule of thumb is that a loud tone masks (hides) a weak tones of higher frequency but not a weak tone of a lower frequency. Thus in tests with tap and noise sounds, one should avoid exciting resonances of lower frequencies than the one of interest. Resonances excited at frequencies above are less disturbing.

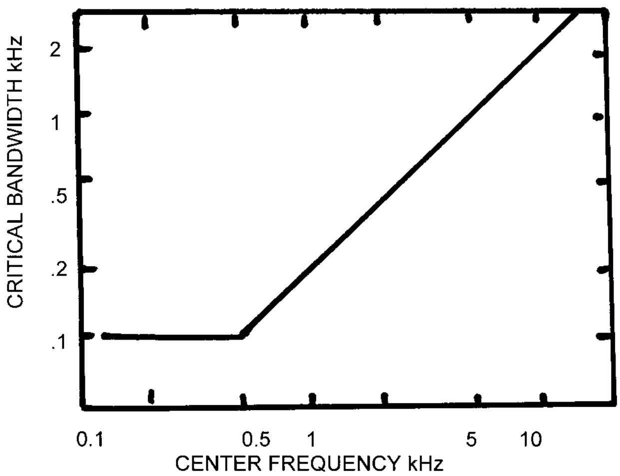


Figure 1.17. Analysis bands, so called critical bands of the hearing. The width of the critical bands in relation to the frequency (from Sundberg).

A played musical tone is not a single tone but a complete spectrum of partials. Therefore the masked threshold for the played tone is fairly complicated to estimate. Each partial will have its own masked threshold, c.f., Fig. 1.16b. The complete, the effective masked threshold of the partial spectrum is the highest partial threshold within each frequency range. Only the partials that reach above the effective masked threshold contribute to the hearing sensation of the partial spectrum. From the masked partial spectrum in Fig. 1.16b one can see that only the first, second, third, eighth and ninth partials contribute to the hearing sensation - the other partials are masked.

CRITICAL BANDS AND ROUGHNESS

The second phenomenon that can be related to the deflection curves for the basilar membrane in Fig. 1.12b, is the roughness of a sound. If two partials are close in frequency, the two partials cannot be heard as separate. One can only hear them together, which gives the sound a sensation of roughness. The roughness sensation appears as the partials are closer spaced in frequency than a CRITICAL BAND of hearing. The widths at the different frequencies for the critical bands are shown in Fig. 1.17. For frequencies below 500 Hz the critical bands are 100 Hz wide but above they are 1/3 of an octave (approximately 25 %) wide.

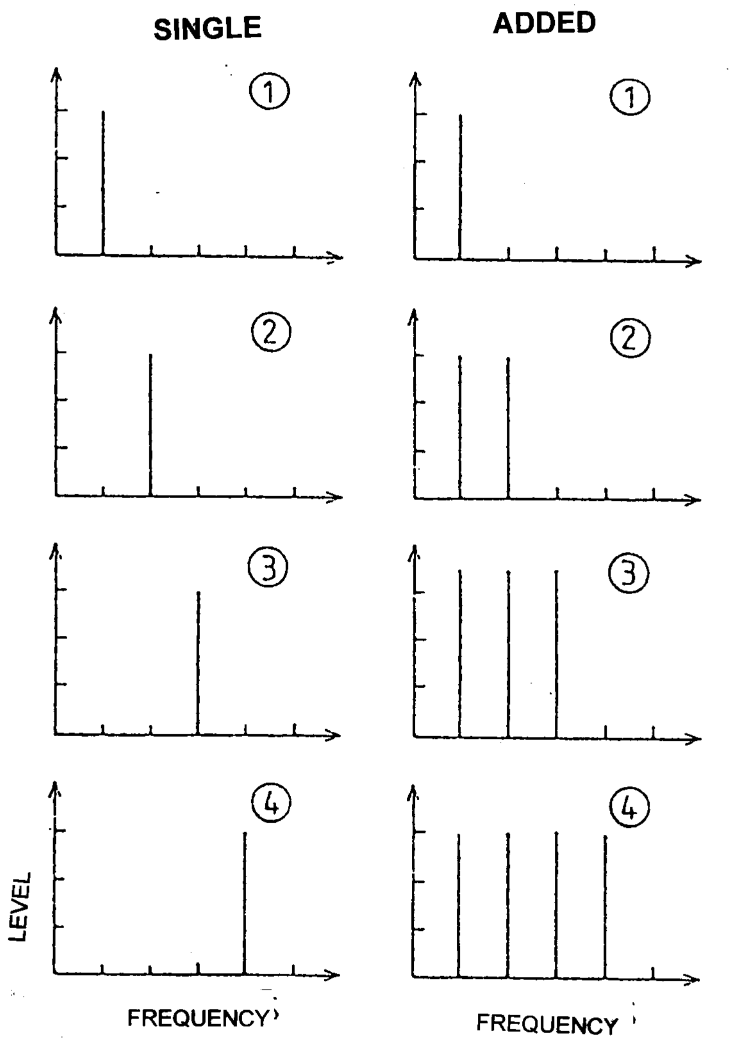


Figure 1.18. Spectra of single tones and the single tones added.

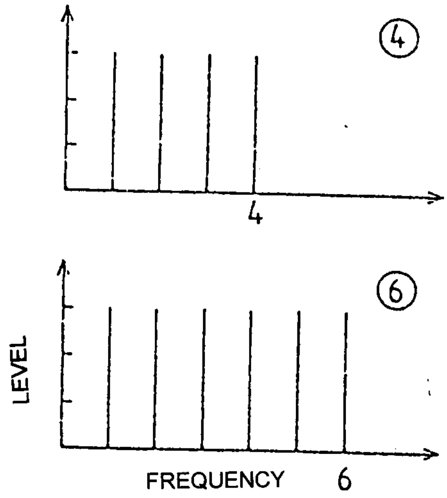


Figure 1.19. Tone spectra with four and six partials respectively - the first spectrum sounds smooth, the second sounds rough.

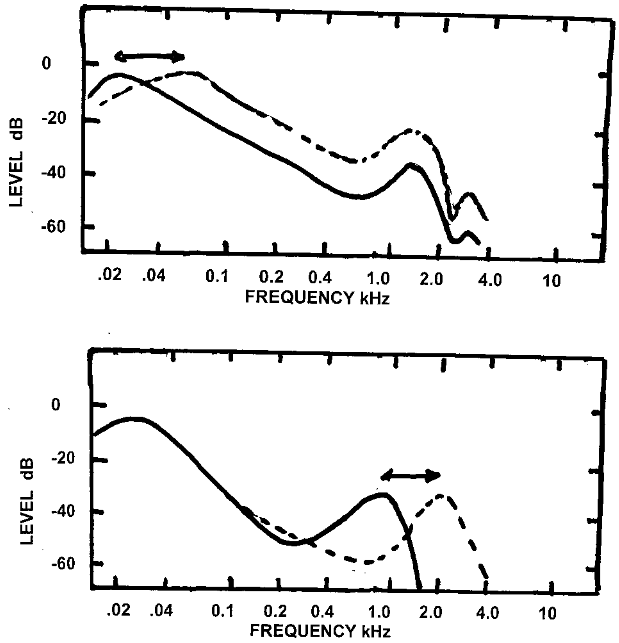


Figure 1.20. Spectra of different vowels (only envelopes, c.f. Fig. 1.9 are drawn, from Fant)

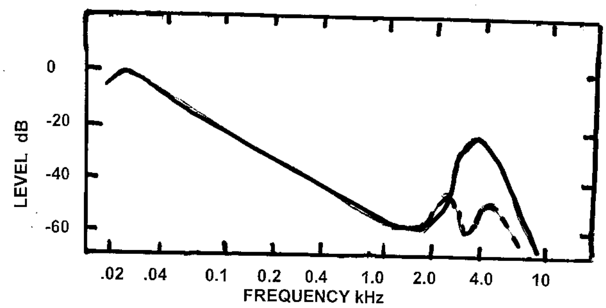


Figure 1.21. Spectrum for a spoken vowel (o in often. dashed line) and sung (with full line, only envelopes drawn from Sundberg).

A simple listening exercise can be prepared as shown in Fig. 1.18. The single partials 1 through 4 give tones with little character and without roughness. If the partials are added a "tone" is heard, still without much character. In the spectrum of the four partials added one can still separate each of the four partials.

Example 1.19. What will happen if we add many partials, can all partials still be distinguished? A little consideration gives that when the critical bandwidth and the frequency separation between partials match, then it should be difficult to separate the partials and roughness will occur. A few calculations show that the bandwidths and the partial separations for musical tones occur up to the fifth partial. Thus we should expect that a played tone with four partials has no roughness but a played tones with six has some roughness. A listening exercise as sketched by Fig. 1.19 will confirm that with six partials a sense of roughness is obtained.

The critical bands of hearing can thus explain the sensation of roughness. Furthermore the musical dissonance can partly be explained by roughness phenomena.

1.8 TIMBRE AND SPECTRUM

The partials of a spectrum results in a character called timbre (often represented as spectrum envelopes). We learn early to recognise differences in timbre of tonal sounds. The vowels of speech are as a matter of fact tonal sounds of different timbre. The timbre of a specific vowel is adjusted in an elegant way. In the vowel in "word" the partial levels follows the full line (i.e. the envelope) in the upper frame of Fig. 1.20. The same vowel is heard also if the fundamental frequency but not the envelope is changed. In the vowel in "cat" the partial levels (the envelope) follow the dashed line. In this case the vowel timbre is independent of the fundamental frequency too. The spectral difference between the two vowels is that the frequency of the leftmost hump has been shifted. By shifting the second leftmost hump the vowel "o" in shoot is shifted to the vowel "e” in three.

The spectral humps are also used to give the sung vowels their timbre and character (not the fundamental frequency), c.f., Fig. 1.21. The male opera singer trains his voice to give strong partials in the range of maximum sensitivity of the hearing. It gives his voice a more brilliant timbre and it comes through the orchestra accompaniment better. This spectrum hump is generally called the singer's formant (a similar spectrum maxim is generally favourable for musical instruments).

As a rule of thumb it can be said that a strong first partial (the fundamental) is necessary for a full sounding timbre. Many and strong high partials give the timbre a more brilliant but also more rough character.

In everyday speech noise and impulse sounds are also included. The fricative consonants such as s, f and sh are filtered noise sounds. Stop consonants such as k, p and t are impulse excited sounds. The character of the fricatives and the stop sounds are formed by different adjustments of the speech organs. The consonant sounds give different timbres and sometimes also a feeling of pitch - similar to the tap and noise sounds used by the violinmaker. It must be pointed out that the sketched ear function is far from complete. Only most fundamental function has been introduced.

1.9. SUMMARY: THE HEARING PROCESS

In the preceding part some of the properties of the hearing process have been presented. The working range of the hearing has been described. Examples on how we perceive sounds have been presented by using common speech sounds. Perception "units" such as pitch, loudness and masking have been introduced.

The presented information on hearing could be used to predict well-known facts further, now not included. It is well known that playing louder, from mf to ff, is not only a turning up of the volume control, it corresponds mainly to an increase of the treble control. However, to show how this is done is outside the scope of the present compendium.

1.10. KEY WORDS:

Measurable units - Frequency, level, spectrum, frequency and level of partials
Perception - units - Pitch, loudness, timbre, hearing threshold, masking, and roughness.