YAMAHA

The Psychoacoustics
of Microtuning

DX7 II·FD/D
DIGITAL PROGRAMMABLE ALGORITHM SYNTHESIZER
SUPPLEMENTAL BOOKLET

Welcome

The third booklet in the microtuning series presented the basic acoustical principles associated with microtonality. This booklet, the fourth in the series, continues the discussion by presenting the fundamental phenomena of psychoacoustics. These phenomena concern the perception of musical sound, and provide additional insight into the effect of microtonal music.

Each section of this booklet describes a major psychoacoustic phenomenon, and presents a set of experiments that you can perform with your DX7 II to demonstrate the effect. In addition, the musical application of each phenomenon is discussed.

Section 1 outlines the experimental procedures used throughout the booklet and presents a step-by-step procedure for creating a patch to use in the experiments.

Section 2 describes the auditory system, which enables us to hear.

Section 3 presents the various phenomena of beats.

Section 4 describes the limit of discrimination and the critical band.

Section 5 discusses the effect of combination tones.

Section 6 describes the phenomena of the missing fundamental and fundamental tracking.

Section 7 presents the just noticeable difference.

For continuing information concerning the DX7 II FD/D, consult AfterTouch, the official publication of the Yamaha Users Group. Many advanced functions will be discussed in its pages in the coming months. There will also be information regarding the availability of other materials concerning more advanced applications. To receive a free copy of AfterTouch every month, send your request to AfterTouch, P.O. Box 7938, Northridge, CA 91327-7938. On your letter or postcard, be sure to indicate that you are the owner of a DX7 II FD/D.

Contents

Introduction

Psychoacoustics is a discipline concerned with the perception of sound. Unlike the study of acoustics, in which results are precise and repeatable, psychoacoustics must contend with the vagaries of human individuality. Each of us will perceive a given sound slightly differently than anyone else. Even so, there are some important general conclusions which have been reached by researchers in this field.

Psychoacoustics plays a very important role in the application of microtuning. By understanding the limits of our ability to perceive and distinguish musical sounds, you will be able to create microtonal music which takes full advantage of these limits without exceeding them to the point of imperceptibility. There are certain perceptual effects which arise not from acoustical phenomena, but from the interaction of neural signals which represent sounds within our brain. These effects can have a strong impact on the perception of music written to employ them.

Experimental Procedures

This booklet describes several experiments that have been performed by researchers in order to demonstrate and evaluate various psychoacoustic phenomena. You may wish to perform these experiments yourself. If so, there are several points of which you should be aware.

1. The experiments described in this section are best performed with electronically generated sine waves (sinusoidal waveforms). Sine waves provide dependable, repeatable perceptions. The effects illustrated by these experiments affect our perception of complex waveforms and depend upon the interaction between the various partials in the timbre.

2. Each of the six operators of either voice in the DX7 II generate sine waves. Algorithm 32 is particularly well suited for these experiments, which generally involve the simultaneous use of two or more sine waves. This algorithm produces six unmodulated sine waves. Each operator can be turned on or off and programmed to produce sine waves of any frequency.

3. The use of headphones is highly recommended. Certain experiments require that each ear be presented with different tones that have not interacted acoustically before reaching the ears. Headphones tend to preclude any distractions as well.

Psychoacoustics Patch

Here is the procedure for creating a patch using algorithm 32 and saving it to the internal memory or a RAM4 cartridge. This patch can be used to perform all of the experiments described in this booklet.

1. Select two voice memory locations and one performance memory location in the internal memory or on a RAM4 cartridge. This is where the voice and performance data for the experimental patch will be saved.

2. Press the PERFORMANCE button.

3. Press the EDIT button.

4. Press the TUNE button (#14) to access the Master Tuning/Memory Protect LCD display.

5. Position the cursor and turn the memory protect parameter OFF for the internal memory (INT) or the cartridge (CRT), depending on where you plan to save the experimental voice and performance data.

6. Insert the ROM cartridge included with your DX7 II into the cartridge slot.

7. Press the CARTRIDGE button (#15) to access the Cartridge Voice & Performance LCD display.

8. Use the -1/+1 buttons to select cartridge bank 2.

9. Press the PERFORMANCE button.

10. Press the DUAL VOICE MODE SELECT button.

11. Press the CARTRIDGE button.

12. Press the A/B button if necessary to select the upper (A) voice.

13. Press the 1-32/33-64 button if necessary to activate the small light above the button.

14. Press the #32/64 button to load INIT VOICE from the cartridge's voice memory location 64 into edit buffer A.

15. Press the A/B button to select the lower (B) voice.

16. Press the 1-32/33-64 button if necessary to activate the small light above the button.

17. Press the #32/64 button to load INIT VOICE from the cartridge's voice memory location 64 into edit buffer B.

18. Press the A/B button to select buffer A for editing.

19. Press the EDIT button.

20. Press the ALGORITHM button (#7).

21. Use the cursor buttons and the data entry slider to select Algorithm 32.

22. Position the cursor at the Voice Name parameter. Hold the EDIT/CHARACTER button as you press the alphabetic keys to type a name for the voice. While holding the EDIT/CHARACTER button, press the CARTRIDGE button for upper case and the INTERNAL button for lower case. Name this voice something like "PSYCH A."

23. Press the DUAL VOICE MODE SELECT button.

24. If you plan to save the patch on a RAM4 cartridge, remove the ROM cartridge. Turn the memory protect switch on the RAM4 cartridge OFF, and insert it into the cartridge slot.

25. Press the INTERNAL or CARTRIDGE button as necessary to specify the memory area in which the voice will be saved.

26. Press the 1-32/33-64 button if necessary to select the range of voice memory locations in which the voice will be saved.

27. Hold the STORE button and press the number button corresponding to the memory location in which you wish to save the voice. Continue to hold the STORE button and press the +1/YES button to confirm your action.

28. Press the A/B button to select buffer B for editing.

29. Repeat Steps 19-27 for the B voice. Name this voice something like "PSYCH B" and save it in a memory location near that of "PSYCH A." For example, RAM4 cartridge voice memory locations 63 and 64 are convenient for this purpose.

30. Press the A/B button to select the upper voice.

31. Press the 1-32/33-64 button and the CARTRIDGE or INTERNAL button as necessary, followed by the number button corresponding to the voice memory location of the "PSYCH A" voice.

32. Press the A/B button to select the lower voice.

33. Press the 1-32/33-64 button and the CARTRIDGE or INTERNAL button as necessary, followed by the number button corresponding to the voice memory location of the "PSYCH B" voice.

34. Press the PERFORMANCE button.

35. Press the EDIT button.

36. Press the MICRO TUNE button (#29) to access the Performance Name LCD display.

37. Hold the EDIT/CHARACTER button as you press the alphabetic keys to type a name for the patch. While holding the EDIT/CHARACTER button, press the CARTRIDGE button for upper case and the INTERNAL button for lower case. Name this patch something like "PSYCHOACOUSTICS."

38. Press the PERFORMANCE button.

39. Press the INTERNAL or CARTRIDGE button to specify the memory area in which the performance patch will be saved.

40. Hold the STORE button and press the number button corresponding to the desired performance memory location. Continue to hold the STORE button and press the +1/YES button to confirm your action.

The patch you have created is now saved. It can be recalled and used to perform the experiments and demonstrate the effects described in this booklet.

2

The Mechanism of Hearing

In order to understand the perception of musical sound, one must first be introduced to the mechanism of hearing. The following presentation is necessarily abbreviated for this booklet, although the anatomy of hearing is actually quite complex.

Our auditory system can distinguish over 30,000 distinct pitches, and is therefore well suited to appreciate microtuning. This section contains descriptions of the major auditory organs.

Outer Ear

Sound waves reaching our ears first encounter the outer ear. This section of the ear is most familiar to us.

Pinna

The part we normally refer to as "the ear" is called the pinna (pronounced pin-a). Sound waves are directed into the entrance of the external canal by the shape and design of the pinna.

External Canal

The external canal continues to focus the sound waves toward the ear drum and the entrance to the middle ear.

Middle Ear

The middle ear consists of the ear drum and three tiny bones that transmit the energy of the sound wave from the ear drum to the inner ear.

Ear Drum

The ear drum, also known as the tympanic membrane, covers the end of the external canal. As sound waves arrive, it moves in sympathetic vibration with them.

Ossicles

The three small bones, known collectively as the ossicles (pronounced os-a-cleese), are called the hammer, anvil, and stirrup. These three bones are connected to each other in a chain from the ear drum to the entrance to the inner ear. As the ear drum vibrates, the sound waves are transmitted mechanically from one bone to the next in the ossicles. At the end of this chain, the sound waves arrive at the entrance to the inner ear.

Inner Ear

The inner ear is responsible for converting the mechanical energy of the sound waves, conveyed by the ossicles, into the electrical energy of nerve impulses. Neurons then send these impulses to the brain.

Cochlea

The stirrup connects to the entrance of the inner ear by means of a small hole at one end of the cochlea (pronounced cock-lee-a). The cochlea is a long, rolled-up tube that resembles a snail shell. This tube is divided in half by the basilar membrane, which runs down the middle of its entire length. There are about 30,000 receptor cells (called "hair cells") arranged in inner and outer rows along the entire length of the membrane. Both halves of the cochlea are connected at the far end, and are filled with a fluid called the perilymph (pronounced perry-limf).

Position vs. Frequency

As the stirrup vibrates at the end of the bone chain in the middle ear, it stimulates vibrations in the perilymph. This in turn sets the basilar membrane into motion resembling that of a waving flag. Amazingly, the membrane vibrates only at a certain location depending on the frequency of the incoming sound waves. At high frequencies, the basilar membrane vibrates only near the stirrup. As the pitch falls, the vibration occurs closer to the far end of the cochlea known as the apex. This selectivity is due to the fact that the basilar membrane is less elastic near the stirrup and becomes more and more so near the apex.

As you may recall from the third booklet in the microtuning series ("The Acoustics of Microtuning"), complex waveforms can be broken down and analyzed as a group of sine waves (called partials). It is quite remarkable that the basilar membrane responds to any complex waveform entering the inner ear by vibrating at the locations which correspond to the frequencies of the component partials. This "spectral analysis" is part of the process by which we perceive a single pitch within a complex waveform consisting of many frequencies.

Hair Cells

The actual conversion from mechanical energy to electrical energy takes place as the hair cells move with the vibration of the basilar membrane. As they move, these cells stimulate nerve endings designed to fire nerve impulses in response to this motion. Our perception of frequency depends on which hair cells are moving. Stimulating the cells near the apex causes the perception of low frequencies. As the position of the stimulated cells moves toward the stirrup, we perceive sounds of higher and higher pitch. This corresponds exactly with the response of the membrane to sound waves of different frequencies.

Properties

There are many interesting properties to be found in this mechanism. The frequency range of 20 - 4000 Hz involves roughly two thirds of the basilar membrane. The remaining range (4000 - 16000 Hz for the average adult) is represented by only one third of the membrane. It is also interesting that, as any frequency is doubled, the position of stimulation moves by a roughly constant amount. This indicates that the position depends on frequency ratios rather than frequency differences.

3 | Beats

The section on acoustics in the third booklet in the microtuning series described the phenomenon of beats. For convenience, that description will be summarized and expanded here.

Acoustic Beats

As you may recall, beats occur when two tones sounding together are very close in frequency. If they are allowed to interact, either in the air between the sound source and our ears or in the electronics of a synthesizer or mixer, we will perceive a single tone periodically growing louder and softer. These cycles of amplitude modulation are called beats.

Perception of a Single Tone

The perception of a single tone is due to the fact that the regions of the basilar membrane that correspond to the two frequencies are found at essentially the same location within the cochlea, and therefore stimulate the same hair cells. The amplitude modulation occurs because the two sound waves are of slightly different frequency, causing their phase relationship to vary. The waves alternately reinforce each other and cancel each other out. This results in a periodic modulation of the overall volume of the sound.

Perceived & Beat Frequency

The frequency of the perceived pitch is the average of the two actual frequencies. This average is obtained by adding the two actual frequencies together and dividing the result by two. The rate at which the beats occur is simply the difference between the two actual frequencies. This rate is called the beat frequency.

Example

For example, suppose that two tones with frequencies of 440 Hz and 442 Hz are sounded simultaneously. These tones are separated by an interval of only 7.85 cents. Under these conditions, you would perceive a single tone with a frequency of 441 Hz (mathematically, 440 Hz + 442 Hz = 882 Hz and 882 ÷ 2 = 441 Hz). The amplitude of this perceived tone would be modulated (that is, would grow louder and softer) at the rate of 2 Hz (442 Hz − 440 Hz = 2 Hz). This is the beat frequency.

Beats in Different Pitch Ranges

Since the phenomenon of beats depends on the difference between two frequencies rather than the ratio, its effect will change as tones in various pitch ranges are played. If the two tones occur in higher ranges, the frequencies must be closer together in order to hear beats. For example, tones at 50 Hz and 45 Hz will beat at 5 Hz; they form an interval of 182.4 cents. The same interval is formed by tones at 500 Hz and 450 Hz. The difference between these frequencies is 50 Hz. They are too far apart to exhibit beats, and are therefore perceived as two distinct tones.

Second Order Beats

The acoustic beats described above are also called first order beats. Second order beats occur between tones separated by nearly a perfect octave. They can sometimes even be detected between tones separated by a mistuned pure fifth or fourth. Such combinations of tones do not vary in overall amplitude as a mistuned unison does. Second order beats are the result of neural processing. They are not evident in frequencies above 1500 Hz.

Binaural Beats

Acoustic beats occur whenever two tones of slightly different frequencies interact acoustically or electronically before they reach our ears. But what happens when two such tones are not allowed to interact before each one reaches a different ear? You might expect that we would perceive each tone distinctly. The fact is that we don't. If two tones are presented separately to each ear, they interact in the neural processing center of the brain. The resulting sensation is called binaural beats.

The effect of binaural beats is similar to (but more subtle and startling than) that of their acoustic counterparts. As before, the frequency of the perceived tone is is derived by taking the average of the original frequencies. The beat frequency is the difference between the frequencies of the two tones. Acoustic and binaural beats differ only in the nature of our perception. The perceived tone seems to move in a circle within the head at a rate determined by the beat frequency. There is no perceived amplitude modulation. As you will see if you perform the experiments described below, binaural beats provide quite an unusual aural experience.

Experiments

The three sets of experiments described below illustrate the concepts introduced in this section.

Acoustic Beats

Acoustic beats are quite easy to demonstrate. The procedure below may be followed with or without the use of headphones.

1. Call up the "PSYCHOACOUSTICS" performance patch.
2. Press the PAN/RIGHT CURSOR button if the light above it is not on. This activates the Pan control.
3. Press the EDIT button.
4. Press the PAN button (#30).
5. Use the -1/NO button to specify Pan mode 0: Mix.
6. Press the OSCILLATOR button (#8).
7. Press the OPERATOR SELECT button #1 (#1).
8. Position the cursor at the Detune parameter.
9. Play C3 on the keyboard. You should hear a single, static sine wave.
10. Use the +1/-1 buttons or the data entry slider to change the Detune parameter value slowly. This will alter the frequency of one of the voices very slightly. You should hear the tone begin to fluctuate in volume. As the Detune value moves farther away from 0, the difference between the frequencies of the two voices becomes greater. As a result, the volume will fluctuate faster.

11. The same effect can be heard by positioning the cursor and altering the Fine Tune parameter. The beat frequency will increase much more rapidly, since each value increment of this parameter represents a larger change in frequency.

12. To demonstrate the frequency dependence of the beat phenomenon, return the ratio value to 1.00 and the detune value to 0.

    a. Play the notes C1 and C#1 (the two lowest notes on the DX7 II keyboard). These tones produce the frequencies 65.4 Hz and 69.3 Hz, respectively. The beat frequency is therefore 3.9 Hz.

    b. Now play B5 and C6 (the two highest notes on the keyboard), which form the same interval as C1 and C#1. These tones produce frequencies of 1975.3 Hz and 2092.8 Hz, respectively. The difference between these frequencies is 117.5 Hz. They are perceived as two distinct tones with no beats.

    c. Play different half steps in various regions of the keyboard. At what point does the beat phenomenon stop and the tones become distinct?

13. Here is another experiment to demonstrate the frequency dependence of beats.

    a. Specify a Detune parameter value of 0 and a ratio value of 1.01.

    b. Press the MICRO TUNE button (#29) to access the Micro Tune LCD display.

    c. Turn the A and B voices ON.

    d. Specify the Pure (Major) preset microtuning.

    e. Play C3 and C4 together. Notice that the beats at C4 are twice as fast as those at C3.

    f. Play several Cs in octaves. Notice the relationship between the beat frequencies.

    g. Play different intervals, such as fifths, fourths, and thirds. Notice the relationships between the beat frequencies.

Second Order Beats

Second order beats are most easily detected if the volume of the higher tone is less than that of the lower tone. The following experiment demonstrates second order beats at the octave.

1. Follow steps 1 through 7 in the procedure for first order acoustic beats.

2. Adjust the Coarse parameter to a value of 2.00.

3. Adjust the Detune parameter to a value of +7.

4. Press the OUTPUT LEVEL button (#10) to access the LCD Level display.

5. Play C3.

6. Adjust the Level parameter downward slightly and restrike C3. Repeat this process until the second order beats are most prominent. You won't hear the new volume level until you restrike the note. If the Level parameter value is below 75 or so, the higher tone will not be heard. The optimum value is around 85.

As you will hear, second order beats are more subtle than first order beats. Try the experiment described above on different notes. Are second order beats easier or more difficult to hear in the extreme ranges of the keyboard?

Binaural Beats

Binaural beats are demonstrated in exactly the same manner as acoustic beats. Follow the procedures above with two very important differences.

1. Headphones must be used to perceive binaural beats. They can be connected directly to the DX7 II headphone output or to a mixer. If you are using a mixer, connect both audio outputs from the DX7 II to two of the mixer inputs. Pan one of the inputs fully to the right and the other input fully to the left.

2. In Step 5 of the "Acoustic Beats" experiment outlined above, specify Pan mode 1: A;on B;on. This will direct voice A to one output and voice B to the other output without allowing them to interact in any way before they reach your ears.

As you perform these experiments, notice that the effect of binaural beats is more subtle than that of acoustic beats. The perceived tone seems to shimmer as it moves around inside your head. Second order binaural beats can also be demonstrated following the procedures described above.

Musical Applications

As you may recall from the third booklet in the microtuning series, beats can occur between various partials in the harmonic spectra of two complex tones sounding simultaneously. This phenomenon is easily demonstrated using tones with linear harmonic spectra. For example, the note a perfect fifth above C is G. If these two notes are played together on an instrument with a linear harmonic spectrum, the second overtone above C should coincide with the first overtone above G. If the fundamental frequencies of these notes are not exactly in the ratio of ⅔, the coincident overtones will not have the same exact frequency. The resulting beats will occur as described above. Similar beats will also occur between many of the other partials in the two spectra.

Tuning & Timbre

The harmonic spectrum of a musical sound can be used to determine the most appropriate tuning for that timbre. For example, playing an equal tempered major triad with a linear spectrum results in many overtone beats, because the partials do not coincide precisely. The overall harmonic quality is quite "rough." However, a major triad that contains a pure third and fifth sounds very "smooth," because many of the partials in the linear harmonic spectrum coincide exactly (and therefore create no beats). This suggests an entire scale for use with linear harmonic timbres based on the ratios found in the linear spectrum.

Linear Harmonic Spectra

Overtone beats occur in instruments with linear harmonic spectra whenever pure intervals are tempered. Keyboard tuners learn to gauge the overtone beat frequencies accurately by ear in order to tune pianos and harpsichords. Beat frequencies can also be used to identify pure intervals, which exhibit no overtone beats. The ability to hear these beats is achieved through practice. "The Equal Beating Temperaments" by Owen Jorgensen is listed in the Bibliography; it describes a procedure by which keyboards can be tuned according to beat frequencies.

Non-linear Harmonic Spectra

The nonlinear spectra of percussion instruments are best suited for different scales and tunings. In general, neither equal tempered nor just tunings are appropriate for such instruments. Intervals and chords played in these tunings usually result in many overtone beats and a characteristic "rough" sound. The relationships between the partials in a nonlinear harmonic spectrum should be used to determine the intervals for more suitable tunings. Such tunings may not have any whole number ratios at all, not even a pure octave. However, there will be little or no overtone beating as intervals and chords are played. The music so performed will have a very "smooth" harmonic quality which simply sounds "right."

Binaural Beats

The musical application of binaural beats has not yet been widely explored. Remember that this phenomenon is evident only when two tones of slightly different frequencies are presented to each ear independently. This suggests an entire genre of music intended solely for headphone listening. If you perform the experiments described above, you will notice that binaural beats provide a rich, almost chorus-like effect. Try playing some music while your DX7 II is set up for the binaural beat experiments.

4 Limit of Discrimination & Critical Band

If you performed the beat experiments described in the previous section, you may have noticed that a sensation of "roughness" replaced the experience of beats as the difference between the frequencies grew. Shortly after that, the two tones became distinct as the difference between the frequencies grew beyond a certain point. This point is called the limit of discrimination. It can also be defined as the minimum difference between two simultaneous frequencies that can still be distinguished as two separate tones.

Roughness

The exact "point of roughness" varies from person to person, but it is generally experienced when the two tones become separated by about 10 to 15 Hz. The limit of discrimination is reached as the difference in frequency continues to increase. It is at this point that the active regions on the basilar membrane corresponding to the two frequencies become sufficiently separated to allow the perception of two distinct tones.

The characteristic "roughness" persists even after the tones become separated by the limit of discrimination. As the difference between the frequencies increases beyond this limit, the sensation of "roughness" becomes one of "smoothness." The point of this transition is called the critical band.

Ranges

Both the limit of discrimination and the critical band extend beyond a minor third in the extreme low range. The limit of discrimination is at its narrowest in the 300 Hz range, where it is roughly equal to a semitone. The critical band reaches its narrowest in the 1500 to 2000 Hz range, where it just exceeds a whole step. Both values slowly increase with the range of the two frequencies after that.

Note:

The relationship between the limits and the frequency range described above is true for sine waves only. Actual instruments produce more complex timbres. This provides our auditory system with additional cues which are effectively used for tone discrimination.

Experiments

Follow the steps below to experience the characteristic "roughness," limit of discrimination, and critical band. Although these terms imply distinct boundaries between the sensations they describe, the actual transitions occur rather gradually.

1. Call up the "PSYCHOACOUSTICS" performance patch.
2. Press the PAN/RIGHT CURSOR button if the light above it is not on.
3. Press the EDIT button.
4. Press the PAN button (#30).
5. Specify Pan Mode 0: Mix.
6. Press the OSCILLATOR button (#8).
7. Press the OPERATOR SELECT button #1 (#1).
8. Position the cursor at the Fine parameter.
9. Play C3.

10. Use the +1/YES button or the data slider to increase the value of the Fine parameter slowly. You should hear the transition from beats to "roughness" as the ratio value reaches 1.04 or 1.05.

11. As the ratio value reaches 1.06 or 1.07, you may be able to detect two separate pitches. You should be able to discriminate between the tones by the time the ratio value reaches 1.10 or so. The value at which you can distinguish two separate tones is your limit of discrimination for C3.

12. The sensation of "roughness" should persist until the ratio value reaches 1.15 or so. It should disappear by the time the value reaches 1.20. Your critical band is the point at which the characteristic "roughness" disappears.

Try this experiment in different pitch ranges. How are your limit of discrimination and critical band affected by performing the experiment while playing C1, C2, C4, C5, or C6?

With Headphones

If you are using headphones, try the following procedure to compare the difference between monaural and binaural stimulation.

1. Play C3 and adjust the ratio value to 1.07. You should hear the sensation of "roughness."

2. Press the PAN button (#30).

3. Specify Pan Mode 1: A;on B;on. This switches the stimulation from monaural (mixed) to binaural.

4. The sensation of "roughness" should disappear. You should hear two distinct tones.

5. Switch back to Pan Mode 0:Mix. The sensation of "roughness" should return.

Musical Applications

The limit of discrimination and the critical band play an important musical role. The "rough" harmonic quality of intervals and chords which are not aligned with their harmonic spectrum is due in part to the interaction of partials lying between these two boundaries. Such partials are separated by 100 to 200 cents or more.

This wide range of "roughness" accounts for the general lack of harmonic integrity found in equal temperament. There are no instruments that exhibit a harmonic spectrum consisting of partials related by the intervals of this tuning. Linear harmonic partials often fall within the range between the limit of discrimination and the critical band as equal tempered intervals and chords are played.

5 Combination Tones

Second order beats are an example of psychoacoustic sensations occurring when two tones are separated by more than the critical band. Another example of such sensations is combination tones. These are first order effects, resulting not from neural processing, but from hair cell stimulation in the cochlea. These frequencies are not present in the original two-tone sound, yet the corresponding regions of the basilar membrane are activated and initiate their perception. This is due to a distortion of the incoming waveform within the perilymph, or cochlear fluid.

Difference Tones

The most evident combination tone is also known as the difference tone. It's frequency is merely the difference between those of the two original tones. Mathematically, if f_1 represents the frequency of the lower tone and f_2 represents the frequency of the higher tone, the frequency of this difference tone is f_2-f_1 (f_2 minus f_1). If f_1 and f_2 are very close, this is nothing more than the beat frequency. As f_2 approaches a perfect fifth above f_1, the difference tone rises to a frequency one octave lower than f_1 (that is, $\frac{1}{2}f_1$). As f_2 reaches an octave above f_1, the difference tone approaches the frequency f_1.

Other Combination Tones

Two other combination tones are generally perceptible. Their frequencies can be calculated in terms of the original two tones as well. They are $2f_1-f_2$ and $3f_1-2f_2$. All three of these combination tones are perceived more easily in a high pitch range. Difference tones are more evident at a high volume level, whereas the other two combination tones are perceptible even at low volume levels.

Experiments

1. Call up the "PSYCHOACOUSTICS" performance patch.

2. Press the PAN/RIGHT CURSOR button if the light above it is not on.

3. Press the EDIT button.

4. Press the PAN button (#30).

5. Specify Pan Mode 0: Mix.

6. Press the OSCILLATOR button (#8).

7. Press the OPERATOR SELECT button #1 (#1).

8. Position the cursor at the Fine Tune parameter.

9. Play C6.

10. Use the data slider to slowly increase the ratio value from 1.00 to 1.99. Notice that the difference tone f_2-f_1 rises from 0 Hz and approaches C6. Notice also the other combination tones. The combination tone $2f_1-f_2$ falls from C6 to 0 Hz as f_2 rises an octave above f_1. The combination $3f_1-2f_2$ falls more rapidly from C6 to 0 Hz as f_2 approaches a perfect fifth above f_1.

11. Combination tones can also be heard if both tones are held at a constant interval.

    a. Adjust the ratio value to 1.50. The two tones will form an interval of a pure fifth ($\frac{3}{2}$).

    b. Play C6. You should be able to hear both of the original tones plus the difference tone (one octave below C6). The combination tone $3f_1-2f_2$ will have a frequency of 0 Hz in this case, but both of the other tones f_2-f_1 and $2f_1-f_2$ will be one octave below C6.

    c. Adjust the ratio value to 1.25. The tones will form an interval of a pure major third ($\frac{5}{4}$).

    d. Play C6. You should be able to hear both of the original tones plus the difference tone (two octaves below C6). The combination tone $3f_1-2f_2$ will be one octave lower than C6 in this case, and the other combination tone $2f_1-f_2$ will be a pure fourth below C6 (sounding G5).

With Headphones

This effect is also evident binaurally using headphones.

1. Press the PAN button (#30) and select Pan mode 1: A;on B;on.

2. Press the OSCILLATOR button (#8).

3. Repeat the experiments outlined in steps 10 and 11 above.

Musical Applications

One of the most important musical applications of combination tones is to reinforce the purity of intervals and chords. Step 11 in the experiments described above demonstrates that two of the three combination tones coincide one octave below the lower member of a pure fifth. Combination tones appear at frequencies of a pure fourth, one octave, and two octaves below the lower member of a pure major third. By combining these intervals, a pure triad is formed. The combination tones reinforce the primary tones in the octaves below the triad.

Musicians can use this effect to verify the tuning of various intervals and chords. It is of particular use to flute and recorder players, whose instruments produce nearly pure sine waves. Paul Hindemith, a twentieth century composer, was well aware of combination tones when he wrote his "Trio" for recorders. The triads at the ends of phrases are greatly enhanced by the combination tones if played with pure intervals. This provides a striking effect for both performers and listeners.

The Missing Fundamental & Fundamental Tracking

As you may recall from the section on acoustics in the third booklet of the microtuning series, complex waveforms can be formed by combining sine waves of different frequencies. If two sine waves with frequencies separated by a pure fifth are combined, the frequency of the resulting complex waveform is half the frequency of the lower sine wave. For example, if two sine waves with frequencies corresponding to a C and a G are sounded together, the frequency of the resulting waveform will be one octave lower than the original C. Our auditory system is sensitive to the frequency of this complex tone. In addition to the original tones, we perceive the frequency of the new waveform as a simple sine wave sounding below the two original tones. This perceived tone is called the missing fundamental.

Harmonic Spectrum

You may also recall that complex waveforms can be analyzed as a combination of sine waves of different frequencies. The compilation of these component sine waves is called the harmonic spectrum. The sine wave of lowest frequency is called the fundamental, and the higher sine waves are called overtones. In a linear harmonic spectrum, the frequencies of the overtones are all whole number multiples of the fundamental frequency.

Fundamental Tracking

As it turns out, the audible combination of any two or more pure tones corresponding to consecutive overtones in the linear harmonic spectrum will result in the perception of the missing fundamental. The frequency of this perceived tone will be that of the fundamental in the spectrum from which the two tones were taken. For example, the linear harmonic spectrum whose fundamental is C1 consists of the tones C1, C2, G2, C3, E3, G3, and so on. If two tones at frequencies corresponding to C2 and G2 are combined, a tone at the frequency of C1 will be perceived. This perceptual phenomenon is known as fundamental tracking. The musical staff below illustrates various combinations of tones that result in the perception of a missing fundamental one octave below middle C.

The missing fundamental is most apparent when consecutive partials in the neighborhood of the third overtone are combined. It becomes less evident when partials from higher in the spectrum are combined. As three or more consecutive partials are added together, the missing fundamental becomes easier to perceive. This leads to the conclusion that fundamental tracking plays a vital role in the association of a single pitch to the complex timbres of acoustic musical instruments.

Frequency

The frequency of the missing fundamental is identical to that of the corresponding difference tone. However, the missing fundamental is a different experience. It is evident at volumes well below the intensity threshold of difference tones. It occurs most readily in a lower pitch range. Physiological experiments have determined that the basilar membrane does not stimulate the hair cells corresponding to the missing fundamental's frequency as it does for difference tones. It also occurs binaurally. All of these facts indicate that the missing fundamental is a second order effect resulting from neural processing.

Experiments

The missing fundamental is not very apparent when two tones corresponding to consecutive partials are played over a long period of time. It becomes much more evident during melodic passages, as you will see in the following experiments.

1. Call up the "PSYCHOACOUSTICS" performance patch.

2. Press the PAN/RIGHT CURSOR button if the light above it is not on.

3. Press the EDIT button.

4. Press the PAN button (#30).

5. Specify Pan Mode 0: Mix.

6. Press the OSCILLATOR button (#8).

7. Press the OPERATOR SELECT button #1 (#1).

8. Position the cursor at the Fine Tune parameter.

9. Adjust the ratio value to 1.50. This will tune one voice a pure fifth above the other voice. The two voices will correspond to the second and third partials in the linear harmonic spectrum, being a pure octave and a pure twelfth above the missing fundamental frequency.

10. Play a series of rapid notes, such as a quick major scale from C3 to C4.

11. Readjust the ratio value to 1.00.

12. Play the same series of notes as you did in step 10. Notice that the sensation of a tone one octave lower than the tones being played disappears when the ratio value is set to 1.00.

13. Repeat steps 9 and 10. Notice that the sensation of a lower tone returns when the ratio value is set to 1.50.

With Multiple Partials

The next experiment demonstrates the reinforcement of the missing fundamental by combining more than two consecutive partials. It continues where the last experiment left off (with the ratio value of operator #1 set to 1.50).

1. Press OPERATOR SELECT button #2 (#2).

2. Set the ratio value to 2.00. This corresponds to the fourth partial, two octaves above the fundamental.

3. Press OPERATOR SELECT button #3 (#3).

4. Set the ratio value to 2.50. This corresponds to the fifth partial, two octaves and a pure major third above the fundamental.

5. Press OPERATOR SELECT button #4 (#4).

6. Set the ratio value to 3.00. This corresponds to the sixth partial, two octaves and a pure fifth above the fundamental.

7. Press OPERATOR SELECT button #5 (#5).

8. Set the ratio value to 3.51. This corresponds to the seventh partial, two octaves and a flat minor seventh above the fundamental.

9. Press the OUTPUT LEVEL button (#10) to access the Level LCD display.

10. Press OPERATOR SELECT button #2 (#2).

11. Set the Level parameter to 99.

12. Repeat steps 10 and 11 for Operators 3, 4, and 5.

13. Press the OPERATOR ON/OFF buttons 1 through 6 (#17 through #22) so that the six numbers below the word "Outlvl" in the Level LCD display are all 0. This will turn all of the partials off except the second partial, which is generated by the other voice.

14. Play a short melodic passage. You should hear only a single sine wave tone.

15. Press the OPERATOR ON/OFF button #1 (#17) to add the third partial.

16. Play a short melodic passage. You should hear the two tones and the missing fundamental.

17. Repeat steps 15 and 16 for operators 2, 3, 4, and 5 (buttons #18-22). The missing fundamental should become stronger after each partial is added.

18. The complex tone can easily be compared with the single sine wave by turning the operators off using the OPERATOR ON/OFF buttons (#17-22).

You may have noticed that the sounds used in this experiment resemble those of a Hammond organ with "drawbars." These drawbars activate and set the volume level of the various partials in the overall timbre. The timbre of the sound produced in this manner depends on the phenomenon of fundamental tracking.

With Headphones

The missing fundamental can also be demonstrated binaurally using headphones.

1. Turn operators 2 through 5 off using the appropriate OPERATOR ON/OFF buttons (#18-21).

2. Press the PAN button (#30).

3. Specify Pan Mode 1: A;on B;on.

4. Repeat steps 6 through 13 in the first experimental procedure above. Each of the two tones should be heard in different ears. The missing fundamental should still be evident though subtle.

Musical Applications

The phenomenon of fundamental tracking is vitally important to the perception of pitch in instruments with linear harmonic spectra. A fundamental frequency is perceived even in spectra entirely devoid of the fundamental partial. This suggests the creation of waveforms with no fundamental component. The auditory system of the listener will supply the missing fundamental.

This psychoacoustical effect is also responsible for the perception of fundamental partials in tones reproduced with low fidelity amplification. Sound systems with limited frequency response, such as car radios, are incapable of producing low frequencies in the bass range. The fact that we can hear a bass part on such a system is due to the effect of fundamental tracking.

Just Noticeable Difference

In addition to the psychoacoustical effects of tones played simultaneously, microtonalists must also consider the perception of tones played sequentially. If two tones very close in frequency are played one after the other, it is possible that they will not be perceived as two different tones. The minimum difference in frequency between two tones which are perceived as different when played sequentially is called the just noticeable difference (JND), or limit of resolution.

General Observations

The JND (Just Noticeable Difference) depends on many factors, including the frequency range, volume, and duration of each tone, and the suddenness of the frequency change. It varies greatly from person to person, and also depends on the degree of musical training. Despite these variables, some general observations can be made. For pure tones of constant volume whose frequency is slowly and continuously varied up and down, the JND is smallest just below 2000 Hz. In this range, a difference of less than 10 Hz is detectable. This is much less than a semitone, and represents a resolution of 0.5%. Above 2000 Hz, the JND increases slightly to 0.6%. In the lowest range, the JND increases to as much as 3%. Sudden changes in frequency result in a JND as much as 30 times smaller than that perceived with slowly varying tones.

It is interesting to compare the JND with the limit of discrimination. The limit of discrimination at 2000 Hz is about 200 Hz. This is about 20 times the value of the JND at the same frequency. This indicates that our ability to distinguish between two sequential tones is much greater than our ability to discriminate two simultaneous tones.

Experiments

1. Call up the "PSYCHOACOUSTICS" performance patch.

2. Press the PAN/RIGHT CURSOR button if the light above it is on. It should <u>not</u> be on for this experiment.

3. Press the EDIT button.

4. Press the MICRO TUNE button (#29) and turn the A and B parameters ON.

5. Press the TUNE button (#14) to access the Micro Tuning LCD display.

6. Hold C3 on the keyboard and press the CARTRIDGE or INTERNAL button. This will select C3 for microtonal editing.

7. Position the cursor at the Fine parameter.

8. Move the data entry slider to the bottom of its range. The resulting value for C3 should be B2 + 21 (4970).

9. Play C3 on the keyboard for one second or so and then release the key.

10. Move the data entry slider slightly until the tuning value reaches B2 + 26 (4975).

11. Play C3 on the keyboard again for one second or so. You will probably not perceive any difference between the frequencies of the two tones.

12. Move the data entry slider back to the bottom of its range.

13. Play C3 on the keyboard again.

14. Move the data entry slider slightly until the tuning value reaches B2 + 27 (4976).

15. Play C3 on the keyboard again for one second or so.

16. Repeat steps 11 through 14, increasing the tuning value by 1 or 2 each time, until you can detect a difference between the two tones. This is your JND for the frequency range of C3. The difference in tuning values will probably be around ten tuning units (which is equivalent to 11.7 cents).

17. Repeat steps 5 through 15 for B5 on the keyboard. The frequency on this note is about 1975 Hz. Your JND should be smaller in this range.

18. Repeat steps 5 through 15 for C1 on the keyboard. Your JND should be largest in this frequency range.

Musical Applications

There are few fundamental musical applications of the JND. Any such applications are melodic in nature, since this effect is produced by two sequential tones. If two notes in a scale fall within the JND, they will not be perceived as different notes when played in a melodic passage. Unfortunately, the JND depends on many factors, including the hearing ability of the listener. This means that there are no consistent means by which the JND can be determined and used musically.

This is of concern only for certain scales in which there are many more than twelve notes per octave. Try playing consecutive keys melodically using the 1/8 tone preset, which consists of 48 notes per octave. It is sometimes difficult to hear the difference between two consecutive notes, particularly in the upper and lower ends of the keyboard. A scale could be designed in which consecutive notes are separated by intervals approaching the JND in each frequency range. Playing all of the notes in such a scale sequentially would result in an effect similar to portamento.

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