

Musical Signal Processing with LabVIEW – Introduction to Audio and Musical Signals

By:
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Online:

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C O N N E X I O N S

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Chapter 1

Perception of Sound¹



	This module refers to LabVIEW, a software development environment that features a graphical programming language. Please see the LabVIEW QuickStart Guide ² module for tutorials and documentation that will help you:
	<ul style="list-style-type: none">• Apply LabVIEW to Audio Signal Processing
	Get started with LabVIEW
	<ul style="list-style-type: none">• Obtain a fully-functional evaluation edition of LabVIEW

Table 1.1

1.1 Introduction

A basic understanding of human perception of sound is vital if you wish to design music synthesis algorithms to achieve your goals. Human hearing and other senses operate quite well in a relative sense. That is, people perceive properties of sound such as pitch and intensity and make relative comparisons. Moreover, people make these comparisons over an enormous dynamic range: they can listen to two people whispering in a quiet auditorium and determine which person is whispering the loudest. During a rock concert in the same auditorium, attendees can determine which vocalist is singing the loudest. However, once the rock concert is in progress, they can no longer hear someone whispering! Senses can adapt to a wide range of conditions, but can make relative comparisons only over a fairly narrow range.

In this module you will learn about **pitch** and **frequency**, **intensity** and **amplitude**, **harmonics** and **overtones**, and **tuning systems**. The treatment of these concepts is oriented to creating music synthesis algorithms. **Connexions** offers many excellent modules authored by Catherine Schmidt-Jones that treat these concepts in a music theory context, and some of these documents are referenced in the discussion below. For example, Acoustics for Music Theory³ describes acoustics in a musical setting, and is a good refresher on audio signals.

1.2 Pitch and Frequency

Pitch is the human perception of **frequency**. Often the terms are used interchangeably, but they are actually distinct concepts. Musicians normally refer to the pitch of a signal rather than its frequency; see

¹This content is available online at <<http://cnx.org/content/m15439/1.2/>>.

²"NI LabVIEW Getting Started FAQ" <<http://cnx.org/content/m15428/latest/>>

³"Acoustics for Music Theory" <<http://cnx.org/content/m13246/latest/>>

Pitch: Sharp, Flat, and Natural Notes⁴ and The Circle of Fifths⁵.

Perception of frequency is **logarithmic** in nature. For example, a change in frequency from 400 Hz to 600 Hz will **not** sound the same as a change from 200 Hz to 400 Hz, even though the difference between each of these frequency pairs is 200 Hz. Instead, you perceive changes in pitch based on the **ratio** of the two frequencies; in the previous example, the ratios are 1.5 and 2.0, respectively, and the latter pitch pair would sound like a greater change in frequency. Musical Intervals, Frequency, and Ratio⁶ offers additional insights.

Often it is desirable to synthesize an audio signal so that its perceived pitch follows a specific **trajectory**. For example, suppose that the pitch should begin at a low frequency, gradually increase to a high frequency, and then gradually decrease back to the original. Furthermore, suppose that you should perceive a uniform rate of change in the frequency.

The screencast video of Figure 1.1 illustrates two different approaches to this problem, and demonstrates the perceptual effects that result from treating pitch perception as linear instead of logarithmic.

Image not finished

Figure 1.1: [video] Two approaches to the design of a frequency trajectory: one linear, and the other logarithmic

1.3 Intensity and Amplitude

Perception of sound **intensity** also logarithmic. When you judge one sound to be twice as loud as another, you actually perceive the **ratio** of the two sound intensities. For example, consider the case of two people talking with one another. You may decide that one person talks twice as loud as the other, and then measure the acoustic power emanating from each person; call these two measurements T_1 and T_2 . Next, suppose that you are near an airport runway, and decide that the engine noise of one aircraft is twice the intensity of another aircraft (you also measure these intensities as A_1 and A_2). In terms of acoustic intensity, the difference between the talkers $T_2 - T_1$ is negligible compared to the enormous difference in acoustic intensity $A_2 - A_1$. However, the **ratios** T_2/T_1 and A_2/A_1 would be identical.

The **decibel** (abbreviated **dB**) is normally used to describe ratios of acoustic intensity. The decibel is defined in (1.1):

$$R_{\text{dB}} = 10 \log_{10} \left(\frac{I_2}{I_1} \right) \quad (1.1)$$

where I_1 and I_2 represent two acoustic intensities to be compared, and R_{dB} denotes the ratio of the two intensities.

Acoustic intensity measures power per unit area, with a unit of watts per square meter. The operative word here is **power**. When designing or manipulating audio signals, you normally think in terms of **amplitude**, however. The power of a signal is proportional to the **square** of its amplitude. Therefore, when considering the ratios of two amplitudes A_1 and A_2 , the ratio in decibels is defined as in (1.2):

$$R_{\text{dB}} = 20 \log_{10} \left(\frac{A_2}{A_1} \right) \quad (1.2)$$

Can you explain why "10" becomes "20"? Recall that $\log(a^b) = b \log(a)$.

⁴"Pitch: Sharp, Flat, and Natural Notes" <<http://cnx.org/content/m10943/latest/>>

⁵"The Circle of Fifths" <<http://cnx.org/content/m10865/latest/>>

⁶"Musical Intervals, Frequency, and Ratio" <<http://cnx.org/content/m11808/latest/>>

Often it is desirable to synthesize an audio signal so that its perceived intensity will follow a specific **trajectory**. For example, suppose that the intensity should begin at silence, gradually increase to a maximum value, and then gradually decrease back to silence. Furthermore, suppose that you should perceive a uniform rate of change in intensity.

The screencast video of Figure 1.2 illustrates two different approaches to this problem, and demonstrates the perceptual effects that result from treating intensity perception as linear instead of logarithmic.

Image not finished

Figure 1.2: [video] Two approaches to the design of an intensity trajectory: one linear, and the other logarithmic

1.4 Harmonics and Overtones

Musical instruments produce sound composed of a **fundamental** frequency and **harmonics** or **overtones**. The relative strength and number of harmonics produced by an instrument is called **timbre**, a property that allows the listener to distinguish between a violin, an oboe, and a trumpet that all sound the same pitch. See *Timbre: The Color of Music*⁷ for further discussion.

You perhaps have studied the concept of Fourier series, which states that any periodic signal can be expressed as a sum of sinusoids, where each sinusoid is an exact integer multiple of the fundamental frequency; refer to (1.3):

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n2\pi f_0 t) + b_n \sin(n2\pi f_0 t) \quad (1.3)$$

where f_0 is the fundamental frequency (in Hz), n denotes the harmonic number, and a_0 is the DC (constant) offset.

When an instrument produces overtones whose frequencies are essentially integer multiples of the fundamental, you do not perceive all of the overtones as distinct frequencies. Instead, you perceive a single tone; the harmonics **fuse** together into a single sound. When the overtones follow some other arrangement, you perceive multiple tones. Consider the screencast video in Figure 1.3 which explains why physical instruments tend to produce overtones at approximately integer multiples of a fundamental frequency.

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Figure 1.3: [video] Why musical instruments produce overtones at approximately integer multiples of a fundamental frequency

Musicians broadly categorize combinations of tones as either **harmonious** (also called **consonant**) or **inharmonious** (also called **dissonant**). Harmonious combinations seem to "fit well" together, while inharmonious combinations can sound "rough" and exhibit **beating**. The screencast video in Figure 1.4 demonstrates these concepts using sinusoidal tones played by a synthesizer.

⁷"Timbre: The Color of Music" <<http://cnx.org/content/m11059/latest/>>

Image not finished

Figure 1.4: [video] Illustration of harmonious and inharmonious sounds using sinusoidal tones

Please refer to the documents Consonance and Dissonance⁸ and Harmony⁹ for more information.

1.5 Tuning Systems

A **tuning system** defines a relatively small number of pitches that can be combined into a wide variety of harmonic combinations; see Tuning Systems¹⁰ for an excellent treatment of this subject.

The vast majority of Western music is based on the tuning system called **equal temperament** in which the **octave interval** (a 2:1 ratio in frequency) is equally subdivided into 12 subintervals called **semitones**.

Consider the 88-key piano keyboard below. Each adjacent pair of keys is one semitone apart (you perhaps are more familiar with the equivalent term **half step**). Select some pitches and octave numbers and view the corresponding frequency. In particular, try pitches that are an octave apart (e.g., A3, A4, and A5) and note how the frequency doubles as you go towards the higher-frequency side of the keyboard. Also try some single semitone intervals like A0 and A#0, and A7 and A#7.

This is an unsupported media type. To view, please see
http://cnx.org/content/m15439/latest/keyboard_pitches.llb

The frequency values themselves may seem rather mysterious. For example, "middle C" (C4) is 261.6 Hz. Why "261.6" exactly? Would "262" work just as well? Humans can actually perceive differences in the sub-Hz range, so 0.6 Hz is actually noticeable. Fortunately an elegantly simple equation exists to calculate any frequency you like. The screencast video of Figure 1.5 explains how to derive this equation that you can use in your own music synthesis algorithms. Watch the video, then try the exercises to confirm that you understand how to use the equation.

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Figure 1.5: [video] Derivation of equation to convert semitones to frequencies

Exercise 1.1

What is the frequency seven semitones above concert A (440 Hz)?

(Solution on p. 6.)

Exercise 1.2

What is the frequency six semitones below concert A (440 Hz)?

(Solution on p. 6.)

⁸"Consonance and Dissonance" <<http://cnx.org/content/m11953/latest/>>

⁹"Harmony" <<http://cnx.org/content/m11654/latest/>>

¹⁰"Tuning Systems" <<http://cnx.org/content/m11639/latest/>>

Exercise 1.3*(Solution on p. 6.)*

1 kHz is approximately how many semitones away from concert A (440 Hz)? Hint: $\log_2(x) = \frac{\log_a(x)}{\log_a(2)}$. In other words, the base-2 log of a value can be calculated using another base (your calculator has log base 10 and natural log).

Solutions to Exercises in Chapter 1

Solution to Exercise 1.1 (p. 4)

659.3 Hz ($n=7$)

Solution to Exercise 1.2 (p. 4)

311.1 Hz ($n=6$)

Solution to Exercise 1.3 (p. 5)

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Chapter 2

M

musical intervals and the equal-tempered scale][mini-project] Musical intervals and the equal-tempered scale¹

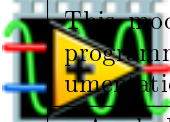
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Table 2.1

2.1 Overview

In this mini-project you will learn about musical intervals, and also discover the reason behind the choice of frequencies for the **equal-tempered** musical scale.

Spend some time familiarizing yourself with the piano keyboard below. Enter the pitch (letter) and its octave number to display the corresponding frequency. For example, **middle C** is C4, and C2 is two octaves below middle C. The frequency 440 Hz is an international standard frequency called **concert A**, and is denoted A4. Concert A is **exactly** 440 cycles per second, by definition.

The black keys are called **sharps** and are signified by the hash symbol #. For example, G#1 indicates the sharp of G1, and is located to the right of G1.

This is an unsupported media type. To view, please see
http://cnx.org/content/m15440/latest/keyboard_pitches.llb

Try the following exercises to make sure that you can properly interpret the keyboard:

Exercise 2.1

(Solution on p. 11.)

What is the frequency of the leftmost black key?

¹This content is available online at <<http://cnx.org/content/m15440/1.1/>>.

²"NI LabVIEW Getting Started FAQ" <<http://cnx.org/content/m15428/latest/>>

Exercise 2.2*(Solution on p. 11.)*

What is the name and frequency of the white key to the immediate left of C7?

Exercise 2.3*(Solution on p. 11.)*

What is the name of the key that has a frequency of 370.0 Hz?

2.2 Deliverables

1. Completed mini-project worksheet³
2. Hardcopy of your LabVIEW VI from Part 4 (block diagram **and** front panel)

2.3 Part 1

One aspect of the design of any scale is to allow a melody to be transposed to different keys (e.g., made higher or lower in pitch) while still sounding "the same." For example, you can sing the song "Twinkle, Twinkle Little Star" using many different starting pitches (or frequencies), but everyone can recognize that the melody is the same.



Download and run `tone_player.vi`⁴, a VI that accepts a vector of frequencies (in Hz) and plays them as a sequence of notes, each with a duration that you can adjust. Listen to the five-note sequence given by the frequencies 400, 450, 500, 533, and 600 Hz (it should sound like the first five notes of "Do-Re-Mi").

Now, transpose this melody to a lower initial pitch by subtracting a constant 200 Hz from each pitch; write the frequencies on your mini-project worksheet⁵:



Modify `tone_player.vi`⁶ by inserting an additional front-panel control so that you can add a constant offset to the array of frequencies. Be sure that you keep the "Actual Frequencies" indicator so that you always know to which frequencies you are listening.

Set the offset to -200Hz, and listen to the transposed melody. How does the transposed version compare to the original? Does it sound like the same melody? Enter your response on the worksheet:

Transpose the original melody to a higher initial pitch by adding 200 Hz to each pitch; write the frequencies on your worksheet:

Set the offset to 200Hz, and listen to the transposed melody. How does the transposed version compare to the original? How does it compare to the version that was transposed to a lower frequency? Enter your response on the worksheet:

Draw a conclusion: Is a **constant** frequency offset a good way to transpose a melody?

2.4 Part 2

In music theory, an **interval** is a standard distance between two pitches. For example, if you play middle C, and then the G above that, you have played a **perfect fifth**. If you start with an F#, then a perfect fifth above that is a C#. The first note you play is called the **fundamental**.

Refer back to the piano keyboard diagram at the top of this page. Each step to an adjacent key is called a **half step** (also known as a **semitone**).

If you play middle C (C4 on the diagram), how many half steps up do you need to go in order to play a perfect fifth interval? Enter answer on your worksheet:

³http://cnx.org/content/m15440/latest/ams_MP-intervals-worksheet.pdf

⁴http://cnx.org/content/m15440/latest/tone_player.vi

⁵http://cnx.org/content/m15440/latest/ams_MP-intervals-worksheet.pdf

⁶http://cnx.org/content/m15440/latest/tone_player.vi

If you begin on A4, which note is a perfect fifth above? Enter answer on your worksheet:

More intervals are listed below; the musical mnemonic may be helpful to hear the interval in your mind:

- Minor 2nd - one half step above fundamental (shark theme from "Jaws" movie)
- Major 2nd - two half steps above fundamental ("Do-Re-Mi," first two notes)
- Major 3rd - four half steps ("Kumbaya", first two notes of phrase)
- Perfect 4th - five half steps ("Here Comes the Bride")
- Perfect 5th - seven half steps ("Twinkle, twinkle, little star", first two notes)
- Major 6th - nine half steps ("My Bonnie Lies Over the Ocean," first two notes)
- Major 7th - eleven half steps ("There's a Place for Us" from West Side Story, first two notes)
- Octave - twelve half steps ("Somewhere Over the Rainbow," first two notes)

Listen to each of these intervals by entering the frequencies from the keyboard diagram. Remember to set your offset to zero. Also, you can silence a note by entering zero frequency. For example, if you want to hear a perfect 6th interval beginning at B3, you should use the frequencies 246.9 Hz and 415.3 Hz (G#4).

2.5 Part 3

Use C4 as the fundamental. Enter its frequency on your worksheet:

What is the frequency of a major 3rd above the fundamental? Enter its frequency on your worksheet:

What is the frequency **ratio** of the interval? Express your result in the form "a : 1", where "a" corresponds to the higher of the two frequencies. Enter the ratio on your worksheet:

Repeat the previous three questions using C5 as the fundamental (remember, C5 is one octave above C4). Enter the three values on your worksheet:

Try this again using A#2 as the fundamental; enter the three values on your worksheet:

Try this again using several different fundamental pitches for another type of interval.

Now, draw a conclusion: Based on what you have experienced about musical intervals so far, can you develop at least part of an explanation for why the frequencies have been selected as they have? Enter your comments on the worksheet:

2.6 Part 4

A variety of scales or tuning systems have been devised for musical instruments, some dating back several millennia. Scales include **Pythagorean tuning**, **just-tempered**, **mean-tempered**, **well-tempered**, (have you heard of Bach's "Well-Tempered Clavichord"?), and **equal-tempered**. For example, a **just-tempered** scale uses the following ratios of whole numbers for the intervals:

- Major 2nd, $9:8 = 1.125:1$
- Major 3rd, $5:4 = \underline{\hspace{1cm}} : 1$
- Perfect 4th, $4:3 = \underline{\hspace{1cm}} : 1$
- Perfect 5th, $3:2 = \underline{\hspace{1cm}} : 1$
- Major 6th, $5:3 = \underline{\hspace{1cm}} : 1$
- Major 7th, $15:8 = \underline{\hspace{1cm}} : 1$
- Octave, $2:1 = \underline{\hspace{1cm}} : 1$

Complete the table above to show each interval as a ratio of the form "a : 1"; enter these ratios on your worksheet:

Modify your VI so that you can enter a single fundamental frequency (in Hz) and an array of interval ratios to play. Be sure to keep the "Actual Frequencies" indicator so that you always know to what frequencies you are listening!

Listen to the scale formed by the following sequence of ratios, and use A4 (440 Hz) as the fundamental: 1, $9/8$, $5/4$, $4/3$, $3/2$, $5/3$, $15/8$, 2. Comment on how well this scale sounds to you (enter your comments on your worksheet):

Transpose the same scale to G4 as the fundamental, and then F4 as the fundamental. Comment on well this scale transposes to different keys (the differences may be rather subtle); enter your comments on the worksheet:

2.7 Part 5

The frequencies on the keyboard diagram above show the piano tuned using the **equal-tempered** scale. An equal-tempered scale sacrifices the pure whole number ratios scheme for intervals, but offers the advantage that a melody transposed to any other key will sound the same. Thus, an equal-tempered scale is a "global compromise" – a given melody will be the same level of out of tune no matter which key is used for the fundamental. The other scales mentioned above will cause a given melody to sound quite nice in some keys, and quite out of tune in other keys.

Derive a mathematical function to calculate the frequencies used by the equal-tempered scale, i.e., given a fundamental frequency and a semitone offset, calculate the frequency. For example, when your formula is presented with the frequency 440 Hz and an offset of 2 (i.e., two semitones above concert A), it should return 493.9 Hz. Be sure to show your complete derivation **process** on your worksheet, and not simply the end result.

Hints:

- Your function should include a fundamental frequency "f" in Hz.
- Your function should include a way to calculate the interval selected by the number of semitones (or half steps) above or below the fundamental frequency.
- Your function should double the frequency when you enter 12 semitones above the fundamental (what should it do when you enter 12 semitones below the fundamental?).

Solutions to Exercises in Chapter 2

Solution to Exercise 2.1 (p. 7)

29.14 Hz

Solution to Exercise 2.2 (p. 8)

B6, 1976 Hz

Solution to Exercise 2.3 (p. 8)

F#4

Index of Keywords and Terms

Keywords are listed by the section with that keyword (page numbers are in parentheses). Keywords do not necessarily appear in the text of the page. They are merely associated with that section. *Ex.* apples, § 1.1 (1) **Terms** are referenced by the page they appear on. *Ex.* apples, 1

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Musical Signal Processing with LabVIEW – Introduction to Audio and Musical Signals

Learn about human perception of sound, including pitch and frequency, intensity and amplitude, harmonics, and tuning systems. The treatment of these concepts is oriented to the creation of music synthesis algorithms. A hands-on project investigates the specific choice of frequencies for the tuning system called "equal temperament," the most common tuning system for Western music. This course is part of the series "Musical Signal Processing with LabVIEW".

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