J. The Moogerfooger

The Physics of Sound and Music, Auditorium in Robinson Hall

October 24, 2002, Photo by former Office Assistant Ruth Maconi

In this chapter we will discuss some general descriptions of sound that are relevant for room acoustics. This material will build on our earlier studies of sound, mainly reflection. Then we will return to the Fourier spectrum, which we have just covered. We will see that some sounds such as bells and gongs include frequencies that are not part of the harmonic series. These sounds are not truly periodic so the harmonic series is not enough to describe them. Such a sound with additional frequency components in its spectrum is call an *inharmonic* sound, one not fully described by its harmonics. These sounds fall under the topic called *inharmonicity*.

Reverb

Reflection is one of the basic properties of waves. When sound waves reflect, we hear echoes. This is a very important property of sound in closed rooms and halls. The various reflections we hear define the acoustics of the room. A room excessive in echoes is not desirable. Enclosures such as basements and dungeons come to mind. Too little reflection gives a dry sound like we are out in an open field.

The speed of sound is 340 m/s = 1100 ft/s. Let's round this off generously to 300 m/s = 1000 ft/s. Sound travels 1 ft in one-thousandth of a second, i.e., 1 ms. It travels 3 ft, which is roughly 1 m, in 3 ms. Someone sitting a couple of meters away from you will hear your voice about 6 ms later. We can take this to be 5 ms since we are estimating. The sound waves leaving you also travel to and reflect off the walls, floor, and ceiling. If you have a rug, the reflections from the floor will be decreased significantly.

Sound hitting a wall nearly a couple of meters away, and reflecting to travel a similar additional distance to reach the hearer may get there 5 ms too late. Sound hitting the ceiling which is farther away than the nearby wall may arrive 10 ms too late. Sound going across the room to the far wall may reach the hearer 15 ms too late. All of the reflected sounds are softer of course. They arrive at the hearer within 20 ms. This makes the room *intimate*. If the first reflected sounds at a small concert hall start coming in to the observer before 20 ms, even though the reflections will continue, the concert hall is judged to be intimate, though not as intimate as an office.

We have learned to expect reflected sounds in rooms and halls. We also get reflections of reflected sound. This can go on for some time, especially in a dungeon. Such persistent reflected sound is called *reverberation* or *reverb*. A strict definition for reverberation or *reverberation time* is the time it takes for the reflections to die down to one millionth of the initial intensity heard by the observer. You might think this is too much to ask for. But our ears are not impressed unless great changes in sound occur. This is necessary if you want to be able to hear a whisper and later a band playing (with the same detector, your ear). Dropping a millionth in intensity is like going from a full blaring orchestra to soft background music or from a forceful voice to a whisper. We will see later that our ears are capable of hearing a change in intensity of more than one trillionth (i.e., a millionth of a millionth)!

To hear some reverb, cup your hands together and speak into them. Although reverberation time is typically too short for us to measure easily, we know when we hear it. You can hear the difference between talking into your hands and talking out in the open. You can imagine the sounds in caves, basements, and dungeons. These latter sounds have much reverberation.

There is a toy called the *Zube Tube* which has a spring about a meter in length inside a tube about the same length. As you talk into it, the sound waves excite the spring. The combination of an excited spring and a cylindrical cavity provides for reverberation. Springs also work in electronic circuits. Sending music in electronic form through a spring causes reverb. Reverb circuits have been designed to enhance the reverberation of the music we hear. You might have a reverb control on your stereo. The circuit introduces reflections electronically and the sound that comes out has more reverb in it. Your music sounds much better than it would if you depended solely on the natural reverb of your room.

Room Acoustics

Room acoustics is very complicated. The experience of sound in a room depends on so many things. The central feature to consider is reverb of course. However, reflections are dependent on where you are in the room, the distance you are from the source, the things in the room, the materials of the walls, etc. Certain materials absorb sound better than others. Special tiles are placed in practice rooms in UNCA's Department of Music to limit sound. These tiles absorb sound so that others in neighboring rooms and the outside halls will not be disturbed as much. Curtains and rugs also absorb sound relatively well. The smoothness of the walls is important. The shape of the room needs to be considered. Remember the dramatic effects in the whispering chamber. The height of the ceiling is crucial. The seats and the people also affect the outcome.

Much goes into the design of auditoriums as you can imagine. Since such planning is so complex, it is really an art, with design parameters evolving throughout the years. The reverberation time gives us a compact way to assess the acoustics of an enclosure. Since some frequencies may reflect better than others, reverb is often reported at specific frequencies such as 125 Hz (low range, bass), 500 Hz (midrange), and 2000 Hz (high range). We are fortunate that all frequencies travel at the same speed. Remember that the speed of sound depends on the medium. Otherwise, we would be in lots of trouble. Some sounds would then arrive out of sync with their supporting sounds.

Two basic descriptions of room acoustics are *intimacy* and *liveness*. We have touched on these already. They are defined below.

Intimacy - presence of reflections reaching hearer within 20 ms after the direct sound.

Liveness - presence of sufficient reverb.

Remember when we discussed the small room, reflections start arriving at the hearer 5 ms after the direct sound, surely less than 20 ms. We say the room is intimate acoustically, regardless of the conversation you are having. However, small rooms tend to be used for actually "intimate" conversations for this very reason.

Now let's go to a larger room like a school auditorium such as the one in *Lipinsky Hall* on campus. Does the hall satisfy the acoustic definition for intimacy? It doesn't have to excel in intimacy like an office, but reflections need to get to us around the 20 ms limit. Remember that sound travels 1 ft (1/3 meter) in 1 ms (millisecond or thousandth of a second).

Suppose we are in the back somewhere 100 ft from the performers. The direct sound gets to us in 100 ms (1 millisecond for every foot to travel). This is one-tenth of a second. The reflections better start arriving 20 ms after this. This means that some of the sound going in other directions better find something to reflect from so that the total distance of the longer path is around 20 ft. The indirect sound waves hitting a wall or the ceiling will travel too far (beyond the allowed 20 ft) by the time it reaches us (in the back) and thereby fail to meet the criterion for intimacy. We have to sit up front for the intimate experience.

On the other hand, the science auditorium has smaller dimensions than the auditorium in Lipinsky. The science auditorium has 180 seats, while the Lipinsky auditorium has about 600. The distance from the front to the back of the science auditorium is only about 40 ft. The sound gets to someone three-fourths of the way toward the back in about 30 ms. Other indirect sound waves have no trouble reflecting off the nearby walls or ceiling, taking paths less than an additional 20 feet. So we easily get reflections within 20 ms. We consider the auditorium "acoustically" intimate, although not as intimate as a smaller classroom.

Other acoustical descriptive words include *fullness*, *clarity*, *warmth*, and *brilliance*. Refer to Table J-1 below. If there is little reverb, we have clarity. This is good for playing Bach. The crisp, clear music of the baroque period (1600-1750) sounds best in rooms where the reverb times are less than 1.5 s. Good reverb times for music of the classic period (1750-1800) are in the range 1.6 to 1.8 s. Reverb times between 1.9 and 2.1 s are best for the full satisfying sounds of the romantic period (1800-1900).

Table J-1. Acoustical Descriptions for Different Amounts and Types of Reverb.

Little Reverb	Much Reverb		
Overall	Low Frequencies	High Frequencies	Overall
Clarity	Warmth	Brilliance	Fullness

For much reverb at low frequencies, the rich bass sounds envelop us with musical *warmth*. Such reverb can enhance the mellow sound of a cello playing in a small ensemble. Reverb at higher frequencies, i.e., *brilliance*, emphasizes instruments that play higher pitches (like flutes and piccolos). The word brilliance, like the others, is subjective. We use words by convention in order to help us describe room acoustics in some standardized way. In all, there are nearly 20 such terms. Two others are *ensemble* (ability of performers to hear each other) and *blend* (a satisfactory mixing of sound for the entire audience).

Reverberation data for four concert halls can be found in Table J-2. The reverberation time is given at three frequencies: 125 Hz (low range, bass), 500 Hz (midrange), and 2000 Hz (high range). The time is given in seconds. Note the shorter reverb times for Philadelphia's *Academy of Music* when compared to Boston's *Symphony Hall*. The great Leopold Stokowski (conductor of the *Philadelphia Orchestra* from 1912-1938) developed a masterful sustaining technique to counter the short reverberation times at the *Academy of Music*. On the other hand, Maestro Serge Koussevitzky of the *Boston Symphony* utilized an abrupt technique to compensate for the longer reverberation times at *Symphony Hall*. Their respective conducting techniques did not serve them well on visiting appearances due to the different characteristics of the halls. So they stopped the visits.

Stokowski conducted the music for the famous Walt Disney film *Fantasia* (1940). Under the direction of Stokowski and later Eugene Ormandy, the *Philadelphia Orchestra* became one of the world's finest orchestras. Eugene Ormandy was known for his interpretation of romantic music such as that of Rachmaninoff. There are old recordings of Eugene Ormandy conducting with Rachmaninoff at the piano, performing Rachmaninoff piano concertos. Ormandy was the conductor of the *Philadelphia Orchestra* from 1938 to 1980.

Table J-2. Acoustical Characteristics of Four Concert Halls (When Occupied).

Concert Hall	Location (City)	Year Built	Number of Seats	Reverberation Time in Seconds		
				125 Hz	500 Hz	2000 Hz
Academy of Music	Philadelphia	1857	2827	1.4	1.5	1.3
Symphony Hall	Boston	1900	2625	2.0	1.9	1.7
Carnegie Hall	New York	1891	2804	2.3	1.8	1.6
Kennedy Center	Washington	1971	2760	2.0	1.6	1.2

L. Beranek, *Concert and Opera Halls: How They Sound* (Acoustical Society of America, Woodbury, NY, 1996), for the above data and conducting story in text.

Inharmonicity

Inharmonicity refers to frequency components of a wave that do not fit into the harmonic series. For example, a 100-Hz ramp wave has Fourier spectral components such as 200 Hz, 300 Hz, 400 Hz, and 500 Hz. These are overtones and members of the harmonic family beginning with the fundamental 100-Hz sine wave. Imagine this ramp wave, but now with additional frequency components 171 Hz and 239 Hz. The wave is no longer a ramp. These frequencies are not in the harmonic series that starts with 100 Hz. These strange inharmonic additions are also called *inharmonic partials*. The overall sound is no longer periodic. If you keep the sound going electronically, the lack of periodicity is experienced as a lack of a well-defined pitch.

We will use a *balanced modulator*, also called a *ring modulator*, to illustrate inharmonicity. The balanced modulator accepts two waves and sends out two modified waves. The modification is understood best by considering input sine waves. When a balanced modulator accepts two pure (sine) input tones, it sends out the sum and difference tones. This is illustrated in Fig. J-1a below.

Fig. J-1a. Balanced Modulator.

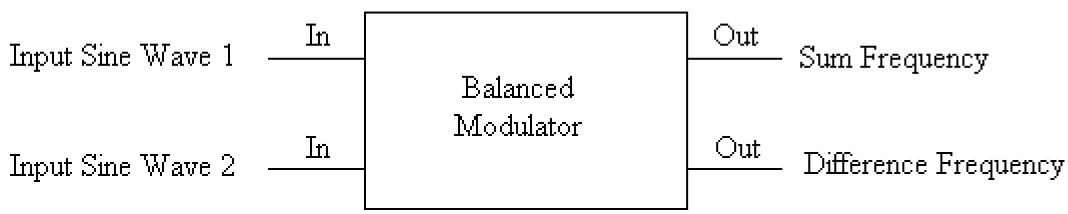
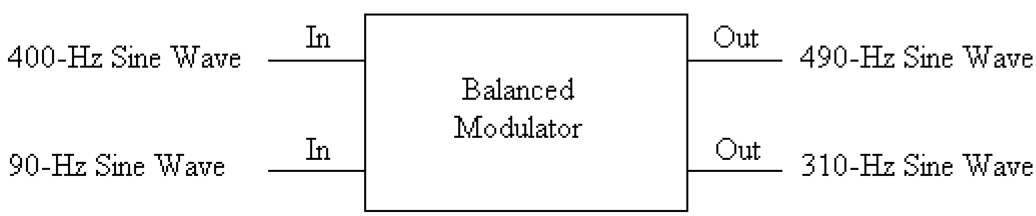


Fig. J-1b. Balanced Modulator Example.



A specific example with numbers is given in Fig. J-1b. The input frequencies are 400 Hz and 90 Hz. The output frequencies are the sum (400 + 90 = 490 Hz) and difference (400 − 90 = 310 Hz). It's important to note that all of these tones are sine waves. The rule applies to sine waves. If you send in one wave which is not a sine wave, then you must decompose it first into sine waves using Fourier analysis. Each harmonic is then added and subtracted with the other input sine wave. Our next example presents such a case.

Let's balance modulate a 600-Hz sine wave with a 50-Hz square wave. We need to think in terms of sine waves so we break the square wave into its harmonic spectrum. The square wave consists of odd harmonics, so we have f, 3f, 5f, and so on. Since f = 50 Hz, the first harmonic is 50 Hz. The third harmonic is three times this, which gives 150 Hz. The fifth harmonic is 250 Hz. Note that the amplitudes of the higher harmonics get smaller. In synthesizing a square wave (last chapter), we used an amplitude of 1/3 for the third harmonic and an amplitude of 1/5 for the fifth harmonic. Since these amplitudes get even smaller and smaller for the higher harmonics beyond the fifth, we can approximate the square wave stopping at H5.

The Fourier sine components for the square wave are listed below in Table J-3. Note that only the first few harmonics of the square are represented since the higher harmonics contribute even less to the sound. The even harmonics are missing for a square wave. Each harmonic of the square wave must be treated separately with the other input, the sine wave. The sum and difference for each harmonic is given in Table J-3. The results are given in Fig. J-2. The relative amplitudes of the original square-wave harmonics are preserved. The frequencies in the spectrum do not form part of a harmonic series. In fact, there is no fundamental. The spectrum is inharmonic.

Table J-3. Balanced Modulation of a 600-Hz Sine Wave and a 50-Hz Square Wave.

600-Hz Input Sine Wave	Square-Wave Harmonic (Hz)	Sum Wave Output (Hz)	Difference Wave Output (Hz)	Relative Amplitude
600	50 (H1)	650	550	1
600	150 (H3)	750	450	1/3
600	250 (H5)	850	350	1/5

Fig. J-2. Spectrum of Inharmonic Output from Above Table.

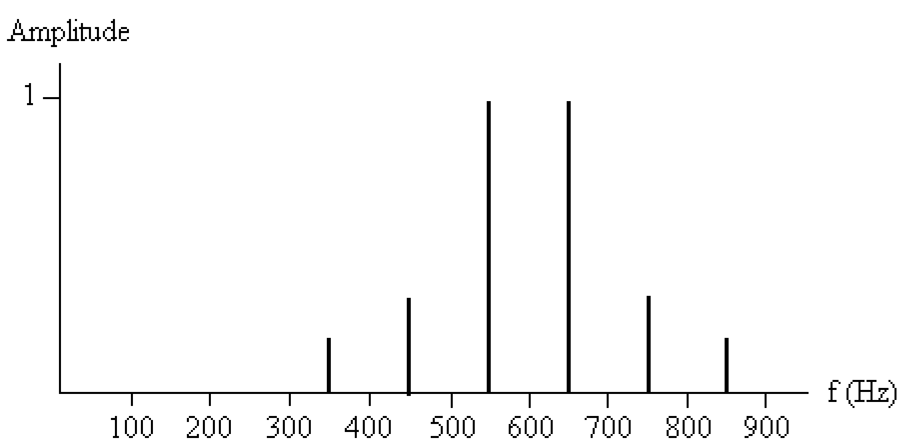


Fig. J-3a illustrates the input sine waves for the problem we just considered. The spectrum for the square wave and the sine appear together. The spectral components are the dotted vertical lines. Fig. J-3b shows the resulting output after balanced modulation. The frequency of each harmonic for the square wave (Wave 1) is added and subtracted from 600 Hz, the frequency of the sine-input wave (Wave 2). The spectral components (inharmonic) are the solid vertical lines.

Fig. J-3a. Input Waves into Balanced Modulator.

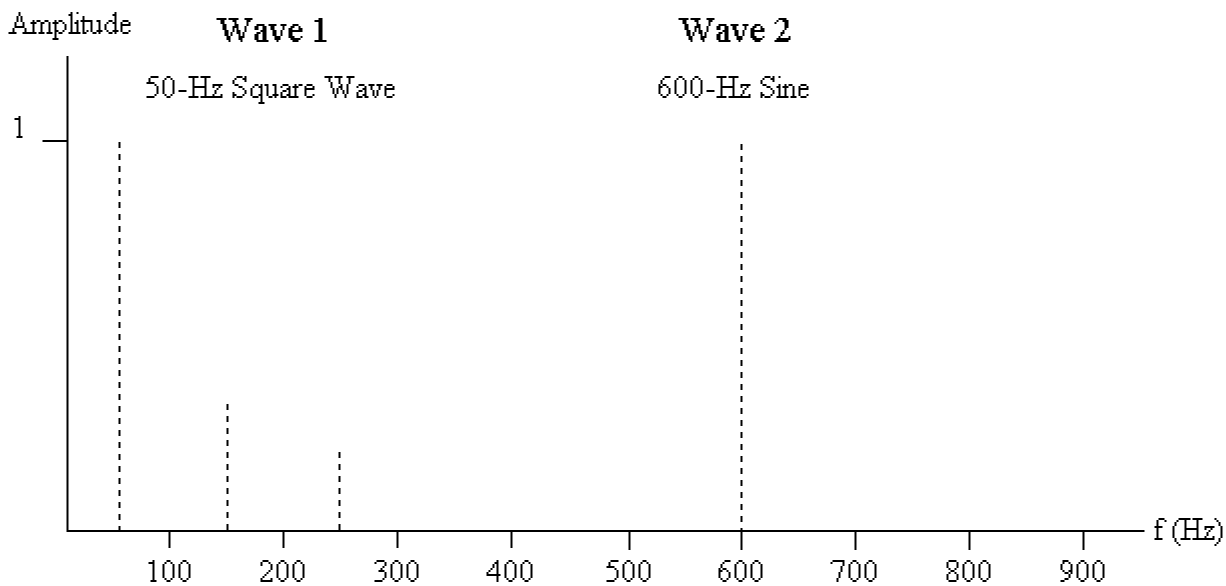
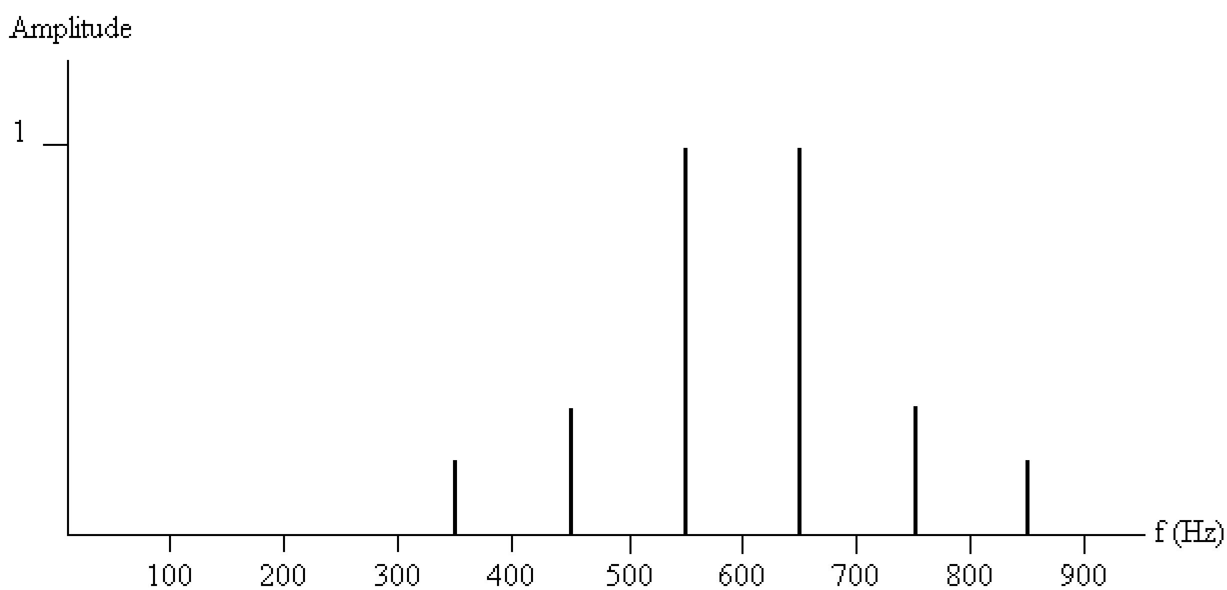


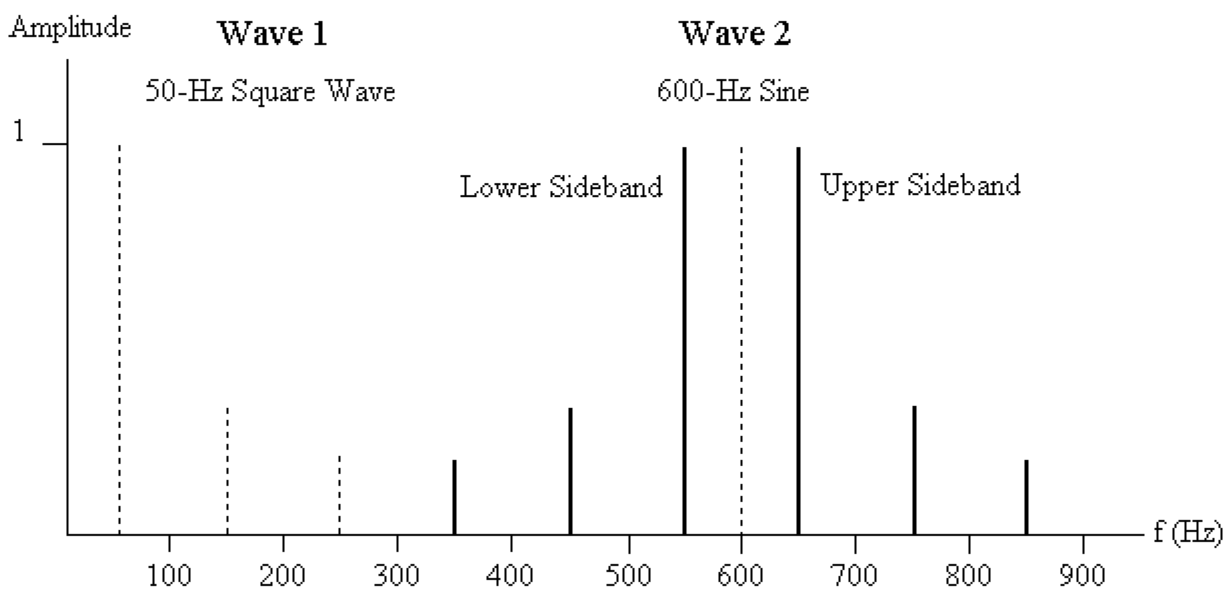
Fig. J-3b. Balanced-Modulated Output Spectrum for Above Input Waves.



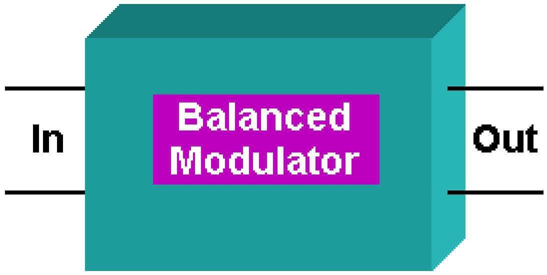
Finally we combine all the steps into one diagram, Fig. J-4 below. The input spectra are dotted, while the output spectrum is solid. Note the mirror-reflection symmetry about the 600-Hz sine wave. The group of frequency components to the right of the 600-Hz sine wave is called the *upper sideband*. The group of frequencies below the 600-Hz sine wave is called the *lower sideband*.

The output spectrum does not consist of a fundamental and its associated overtones as we find for periodic waves. In fact, as we noted, there is no fundamental. The spectral components 350, 450, 550, 650, 750, and 850 Hz do not exhibit the characteristic relationships of the harmonic series, i.e., f, 2f, 3f, 4f, etc. The balance-modulated sound is inharmonic. Any sound that is not periodic is technically inharmonic. However it is interesting to note sounds that are nearly periodic. Such examples of inharmonic sounds include bells, chimes, and gongs. The Moogerfooger 102 is built on principles of blalanced modulation. See your Power Notes for more on the Moogerfooger.

Fig. J-4. Balanced Modulation (50-Hz Square Wave and 600-Hz Sine Wave).



Some Questions



A 1050-Hz sine wave is balanced modulated with a 50-Hz ramp wave. Give the difference and sum frequencies for each Fourier component of the ramp wave balanced modulated with the sine wave. Enter amplitudes as fractions such as 1/2 when appropriate. Do NOT use decimals. Make sure you give the difference and sum frequency even though the amplitude may be zero. The zero amplitude means that these components will not be present in the output wave.

Part	Harmonic	Difference Wave (Hz)	Sum Wave (Hz)	Relative Amplitude	Hints
a	1				1050 - 50, 1050 + 50, 1
b	2				1050 - 100, 1050 + 100, 1/2
c	3				1050 - 150, 1050 + 150, 1/3
d	4				1050 - 200, 1050 + 200, 1/4
e	5				1050 - 250, 1050 + 250, 1/5

--- End of Chapter J ---

