TAKING UP RESONANCE

finding room modes on your computer

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For quite a long time I have wanted to try a subwoofer in my audio system at home because I like listening to large orchestras and pipe organs. A long organ pipe can put out large amounts of energy at very low frequencies, and CDs can carry high-level signals at frequencies as low as 10 Hz (Table I). I wanted to hear some of that bass energy in my listening room!

In selecting a subwoofer though, it's important to know that each room has its own signature frequency response and low-frequency cutoff. At the frequencies that subwoofers handle, the room's response can strongly dominate that of the loudspeaker [1]. We need to select the most appropriate subwoofer in terms of its low-frequency response. The loudspeaker and room act together as a resonant *system*—both affect what we hear.

Many resonant effects can be easily visualized by watching a vibrating guitar string. If you pluck that string, it will vibrate at its own natural (resonant) frequency, which depends, among other things, on its length. As the energy in the string bounces back and forth against its fixed ends, a pattern is set up due to resonance. If you look closely, you can see that the center of the string vibrates most and the ends not at all. Though the string itself is vibrating, the pattern (the locations of the string's maximum and minimum vibration points) is stationary. This is a *standing wave.*

The frequency at which the whole length of the string vibrates is called its *fundamental* and is the string's lowest natural frequency. But the string will also vibrate at frequencies that are integral multiples of that fundamental frequency called *harmonics.*

Frequency and wavelength are inversely related. When one is large, the other is small, and vice versa. So the harmonics, being higher in frequency, have shorter wavelengths than the fundamental. For example, the wavelength of a second harmonic is just half the length of the original.

Rooms, too, have resonances. But while the resonances of guitar strings are usually excited by the guitarist's fingers, room resonances are excited by sounds of similar frequencies. Instead of vibrating between the endpoints of a string, the sound energy in a room bounces back and forth between rigid wall surfaces. And sounds at the room's resonant frequencies also set up standing waves, with points of high and low sound pressure.

Because of this, perception of bass frequencies in small, regularly shaped rooms can be highly variable and depends on where you are relative to standing waves generated by resonances. The room's response can be strongly imposed on a loudspeaker's output. That's why moving either the listener or the loudspeaker just a few feet can sometimes make a considerable difference in bass loudness.

The lowest (fundamental) resonance of a room occurs at the frequency whose wavelength is equal

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to twice the room's length. (The factor of two is involved because we can have a *half*-wavelength standing wave.)

The lowest resonant frequency of a room can be obtained by dividing the speed of sound by twice the room's length. Taking the speed of sound as 1,141 feet per second (it actually varies slightly with the temperature, altitude, and humidity), we get a figure of 29 Hz for a room 20 feet long. *This is the lowest frequency at which we can generate loudness with reasonable efficiency in a room this size.* The only way to lower it would be to increase the room's length.

Below this frequency, we can't establish even a half wavelength in the room, so a standing wave can't exist. As a result, there won't be a point of maximum acoustic pressure where a loudspeaker could be most efficiently coupled to and excite the lower frequency.

A subwoofer whose frequency response rolled off below 29 Hz would be adequate to excite the lowest frequency in this room. There are, of course, other important subwoofer parameters to consider besides frequency response.

RESONANT MODES

Since a rectangular room has three principal dimensions (length, width, and height), it will have three different fundamental resonant frequencies, as well as harmonics of higher frequencies (which have shorter wavelengths). Energy can bounce off all surfaces and in all directions in a room, setting up numerous combinations of resonances (fundamental and harmonics) related to

The room's *length determines* the lowest *frequency* at which *a subwoofer can* work efficiently.

the room's geometry. These combinations are called *modes.*

The strength of each mode is different and the entire collection of modes defines a room's frequency response. Different standing-wave patterns of sound energy can be set up in a room depending on which modes are excited.

At low (base) frequencies, the modes are generally separate and distinct. At high frequencies, they are so numerous and bunched together that they form a continuum. We will be looking at only the low-frequency modes here.

Any resonant mode of a room may be calculated from the formula:

$$F = \left(\frac{C}{2}\right) \times \sqrt{(i/L)^2 + (j/W)^2 + (k/H)^2}$$

where F is the frequency of the mode in hertz, C is the speed of sound in air, and L, W, and H are the room's length, width, and height in feet.

If all we really *cared about was* resonance, we'd *put our speakers* in the center *of the room.*

TABLE I—*Compact Discs with audible components below 32 Hz. (Louis D. Fielder and Eric M. Benjamin, "Subwoofer Performance for Accurate Reproduction of Music,"* Journal of the Audio Engineering Society, *June 1988.)*

FREQUENCY, Hz		COMPOSER/		RECORD	CATALOG
FOR 120 dB	FOR 110 dB	ARTIST	SELECTION	LABEL	NUMBER
10	12.5	Tchaikovsky	1812 Overture	Telarc	CD-80041
16.5	16.5	Dupré	Symphony in G Minor	Telarc	CD-80136
15	17.5	Grofé	Grand Canyon Suite	Telarc	CD-80086
18	18	Hindemith	Organ Sonata No. 1	Argo	417159-2
18.5	18.5	Jongen	Symphonie Concertante	Telarc	CD-80096
12.5	22	Flim & The BBs	Big Notes	dmp	CD-454
16.5	22	Strauss	Also sprach Zarathustra	Telarc	CD-80106
22	22	Bach	Kyrie, Gott heiliger Geist	Telarc	CD-80097
24	24	Saint-Saëns	Symphony No. 3	Telarc	CD-80051
25	25	Williams	"Star Wars" Theme	Telarc	CD-80094
19	25	Bach	Toccata and Fugue in D Minor	Telarc	CD-80088
29	29	Billy Cobham	Warning	GRP	GRD-9528
29	29	Various	Movie soundtrack, "Country"	Windham Hill	WD1039

TABLE II—*Room modes for a room 20 feet long, 11 feet wide, and 8 feet high, as calculated by the program in Table III.*

MODE (L,W,H)			FREQ (Hz)	MODE (L,W,H)			FREQ (Hz)
0	0	0	0	0	0	1	71
0	0	2	143	0	1	0	52
0	1	1	88	0	1	2	152
0	2	0	104	0	2	1	126
0	2	2	177	1	0	0	29
1	0	1	77	1	0	2	146
1	1	0	59	1	1	1	93
1	1	2	155	1	2	0	108
1	2	1	129	1	2	2	179
2	0	0	57	2	0	1	91
2	0	2	154	2	1	0	77
2	1	1	105	2	1	2	162
2	2	0	118	2	2	1	138
2	2	2	186				

The variables i, j, and k require a bit more explanation. Together, they form a three-part "mode number" that defines a mode's relationship to the dimensions of the room; i is associated with the length, j with the width, and k with the height. These numbers take on only integer values such as 0, 1, 2, 3, etc. For example, the lowest room mode would be 1, 0, 0, representing the fundamental of the length-related resonance, with no contribution from the width and height; the 0, 2, 1 mode would represent the second harmonic of the width-related resonance mode and the fundamental of the floor-to-ceiling resonance.

The mode numbers i, j, and k each take on integer values, 0, 1, 2, 3, etc., and are associated with the resonant modes of the length, width, and height, respectively, of the room [2]. Table II is a computer printout of the lower modes of my listening room. From it, you can derive the following examples:

1. My listening room measures 20 × 11 × 8 feet. The lowest room mode, at 29 Hz, is i = 1, j = 0 and k = 0 (abbreviated 1, 0, 0). Since j, which corresponds to the width, is zero, and k, which corresponds to the height, is zero, those dimensions do not contribute to this mode.

2. The next lowest frequency mode, 0, 1, 0, involves only the fundamental frequency associated with width (j = 1), which is 52 Hz.

3. The next two modes are 2, 0, 0 at 57 Hz and 1, 1, 0 at 59 Hz and involve the second harmonic of length and the fundamental of both length and width, respectively. They are close to mode 0, 1, 0 in frequency and might combine with it to some extent.

Computer Program

The above formula is tedious when evaluating many modes, so I wrote a short computer program (Table III) that calculates modes in any regularly shaped room.

It is desirable to have a large number of closely spaced (but not identical) resonances in a room, as they will smooth the overall room response rather than appear as individual resonances. It is the lower modes that are responsible for conveying most of the low-frequency energy in a room.

Optimizing Loudspeaker Locations

The best place to excite the largest number of modes is from the corners of a room. This is the point of highest sound pressure for all of the room's modes, including the lowest one. It is where a loudspeaker is most efficiently coupled to the room's resonant modes. Since a subwoofer is used to excite the lowest room modes (typically below 75 or 100 Hz) it should be placed there [3]. Placing full-range speakers in corners unbalances overall response and causes boomy bass. But when only subwoofers are placed there, the response can be balanced by turning down the power in the subwoofer channel, reducing potential distortion in both the bass amplifier and the subwoofer.

If all we cared about was regular frequency response, the ideal position for the main speakers would be at the precise center of the room—halfway up from the floor as well as centered over it—where it would excite the fewest possible modes and where the room's irregular effects on response would be at a minimum. The room's ex-

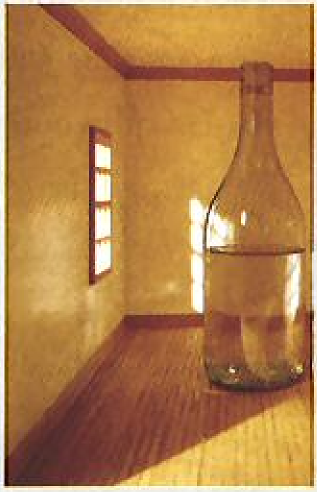
TABLE III—*This BASIC-language program computes the whole-number frequency of the lower room modes, from 0,0,0 to 2,2,2, and shows them on the screen and, if desired, the printer. Table II was generated by this program. Most personal computers come with some form of BASIC interpreter or compiler, such as BASICA, GWBASIC, QuickBASIC, QBASIC, TurboBASIC, Applesoft BASIC, etc.*

You can type and enter the program in the BASIC environment. An easier way is to use a word processing program (which makes typing and editing easier) that can save files in ASCII text format for later BASIC use.

When entering the program, do so *exactly* as it is shown here and save the file under the name ROOMODE.BAS.

```
1 REM: PROGRAM COMPUTES FREQUENCIES
OF NORMAL ROOM MODES
10 CLS
20 PRINT "INPUT ROOM LENGTH, WIDTH,
AND HEIGHT (IN DECIMAL FEET),
SEPARATED BY COMMAS:"
30 INPUT L, W, H
40 PRINT
50 PRINT "MODE (L,W,H)"; TAB(15);
"FREQ(HZ)"; TAB(41); "MODE (L,W,H)";
TAB(55); "FREQ(HZ)"
60 FOR I = 0 TO 2
70 FOR J = 0 TO 2
80 FOR K = 0 TO 2
90 FREQ = 571 * SQR((I/L) ^ 2 + (J/W)
^ 2 + (K/H) ^ 2)
95 FREQ = INT (FREQ + 0.5)
100 PRINT I; J; K, FREQ;
109 REM: (LINES 110-120 FORCE 2-COLUMN
DISPLAY SO NUMBERS WON'T SCROLL OFF)
110 COL = COL + 1
120 IF COL = 2 THEN COL = 0: PRINT
PRINT TAB(41);
130 NEXT K
140 NEXT J
150 NEXT I
160 PRINT: PRINT
170 PRINT "(TO PRINT, PRESS SHIFT &
PRT-SC KEYS TOGETHER WITH PRINTER ON
LINE)"
```

When using the program, enter room dimensions carefully—this program has no error trapping. This program should give you a good general picture of your room's resonances and help you select a subwoofer to use in that room.



Calculating room *modes can be* tedious, so here *is a computer* program to figure *it out for you.*

There's not much *sense paying for* a 10-Hz subwoofer *if it will be* used in a 29-Hz *listening room.*

TABLE IV—*Frequencies of multiple ("degenerate") modes in a cubical room 20 feet on a side.*

FREQUENCY (Hz)	NUMBER OF MODES
29	3
40	3
57	3
64	6
70	3
81	3
86	3

act center is at a low-pressure point for most of a room's modes, which makes them more difficult to excite. Typically, only about 10% of the total modes will be easily excited there. Only those modes that have only even mode numbers (such as 2, 2, 2 or 0, 2, 4) will be well excited by a center-mounted speaker [3].

However, resonances are not the only considerations. In the real world, such factors as minimizing early reflections, maintaining separation between the two speakers of a stereo pair, traffic patterns in the room, and practical seating positions take precedence over this ideal.

TABLE V—*Room-dimension ratios based on third-octaves (see text).*

	H	:	W	:	L		H	:	W	:	L
Small room	$2^{0/3}$	:	$2^{1/3}$	:	$2^{2/3}$	=	*1*	:	*1.25*	:	*1.6*
Average room	$2^{0/3}$	:	$2^{2/3}$	:	$2^{5/3}$	=	*1*	:	*1.6*	:	*2.5*
Low ceiling	$2^{0/3}$	:	$2^{4/3}$	:	$2^{5/3}$	=	*1*	:	*2.5*	:	*3.2*
Long room	$2^{0/3}$	:	$2^{1/3}$	:	$2^{5/3}$	=	*1*	:	*1.25*	:	*3.2*

As with most things, loudspeaker placement is a compromise. Putting speakers at the room's center (as closely as we can approximate it in practice) will yield smoothest frequency response and best stereo imaging—but bass response is compromised there. For the strongest bass response, the corners are best. Use of a subwoofer allows us to take best advantage of both locations.

Room Shapes

If any of a room's dimensions are too close to being whole number (integer) ratios of each other, two or more "degenerate" modes at or close to the same frequency will occur. The resonant rise at these frequencies will be much more than at any frequency corresponding only to a single mode, because the degenerate modes combine their effects. Also, their standing waves will be spread out over a larger volume of the room, making them harder to avoid.

The more symmetrical a room is, the more irregular its response will be. The worst case is a cubical room, whose three dimensions are equal, causing many of the modes to wind up at the same frequencies. This leads to very strong standing waves at just a few widely spaced frequencies, causing very ragged room response. Such a room would have large amplitude peaks and wide frequency gaps between peaks. Also, such a room would have no central "sweet spot" where few modes are excited.

Up to mode 2, 2, 2, there are 26 modes in a room. In a 20 × 20 × 20 foot cubical shape room, there are seven frequencies at which multiple modes exist (Table IV).

In a cubical room, 24 of the 26 modes (92%) are degenerate. In the worst case, at 64 Hz, six modes combine to produce a very large resonant peak in the room. This is a listening-room shape to avoid! Round and elliptical rooms have this kind of (and other worse) problems.

Suggested ratios for room dimensions are based on third-octaves, $2^{n/3}$, where n is any integer not divisible by 3 (e.g., 0, 1, 2, 4, 5, 7, etc.)[4]. These ratios give well-spaced room mode frequencies. Table V shows some examples.

We pay a great deal of attention to loudspeaker frequency response. But we often don't realize that the room also has a very strong effect on what we hear, especially at low frequencies. So we need to consider both together. The computer program in Table III lets you easily find out what these effects are in your room. This can help you make intelligent choices about loudspeaker performance and positioning and about selecting a subwoofer that is appropriate for your room. After all, there's not much sense paying for a 10-Hz subwoofer in a 29-Hz room. A

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