Loudspeaker Placement Part I

By Bohdan Raczynski

At some stage you will arrive at the end of the loudspeaker system design process. It is probably fair to assume, that a large effort went into designing and building the "perfect system", possibly having anechoic flat frequency response from 20Hz to 20kHz and many other desired and unique features.

Once you have been through the process, you are likely to conclude, that a lot of the intellectual and physical and financial effort went into extending the low end of the system's frequency response and achieving smooth and balanced mid- and high-end output.

There is one more challenge to consider on the way to actually enjoying the music: the listening room acoustics. Room acoustics issues are complex and for many of us the "learning factor" will be significant. Absorption, reflection and diffusion are the issues to be considered, together with ray-tracing and modal analysis. In the worst case, misunderstanding in this area may obliterate most of the effort I mentioned above and well design system will loose much of its character. The room characteristics can never be removed from the listening experience and they must be considered if you are serious about what you hear. There are "rules of thumb' and a lot of common knowledge in placing the loudspeakers, but when it comes to showing the actual pressure distribution within The room and predicting resonances for complex shape rooms, the situation is quite different. So, what would be this "worst case" scenario ?. Amongst many possible factors, I pick the following three:

1. Wrong positioning of the loudspeakers.
2. Wrong location of the listening position.
3. Poor room acoustics.

As a minimum solution to the above problems I would consider avoiding (1) and (2) and optimizing (3). The remainder of this article will proceed along this idea, keeping the complexity on introductory level.

Mid-frequencies Problem

From the theoretical point of view, below 300 Hz, the average listening room must be considered as a resonant cavity. In this frequency range, reflections result in standing waves and the room becomes a resonating chamber. Above 300Hz the Ray-Tracing Model becomes more useful. Here, I assume that the ray's incident angle is the same as the reflection angle. In the home situation, the shape and size of the listening room is already fixed.

For the purpose of reviewing the issues associated with room acoustics in mid-frequency range, I would like to start with a simple case depicted in Fig 1. Let's assume that there are only two audio paths arriving at the test microphone.

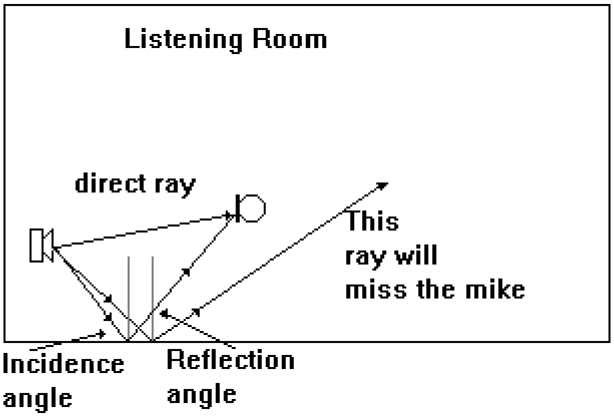
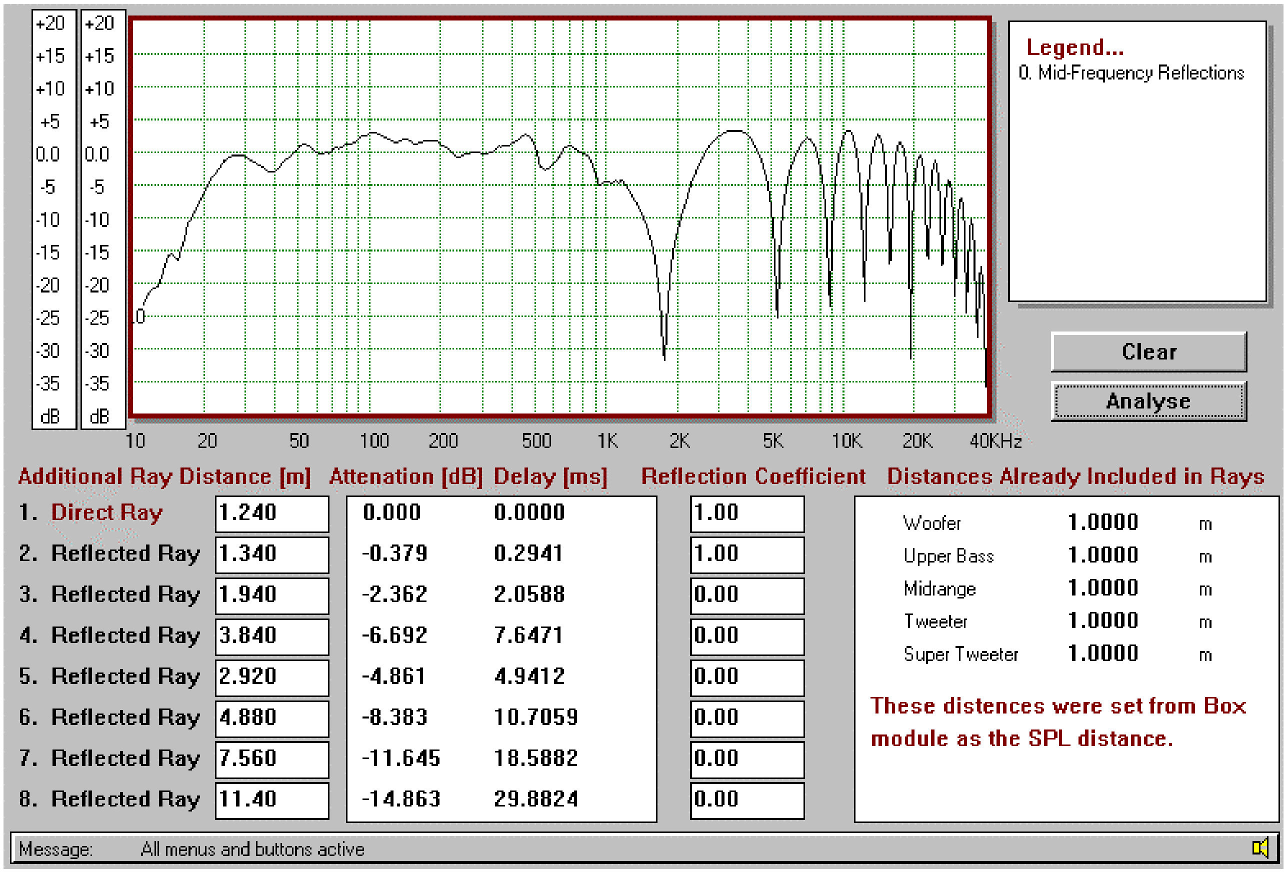


Figure 1. Incident and reflection angles.

If the reflecting surface is hard, there is no phase change between incident and reflected rays. Please note, that the two angles are equal, so not every ray will reach the microphone. Figure 1 depicts the case, where two rays are combining at the microphone: (1) direct ray and (2) single ray reflected from the floor. The difference in length between these two paths is 10 cm.



Additional Ray Distance [m]		Attenation [dB]	Delay [ms]	Reflection Coefficient
1. Direct Ray	1.240	0.000	0.0000	1.00
2. Reflected Ray	1.340	-0.379	0.2941	1.00
3. Reflected Ray	1.940	-2.362	2.0588	0.00
4. Reflected Ray	3.840	-6.692	7.6471	0.00
5. Reflected Ray	2.920	-4.861	4.9412	0.00
6. Reflected Ray	4.880	-8.383	10.7059	0.00
7. Reflected Ray	7.560	-11.645	18.5882	0.00
8. Reflected Ray	11.40	-14.863	29.8824	0.00

Distances Already Included in Rays

Woofer	1.0000	m
Upper Bass	1.0000	m
Midrange	1.0000	m
Tweeter	1.0000	m
Super Tweeter	1.0000	m

These distences were set from Box module as the SPL distance.

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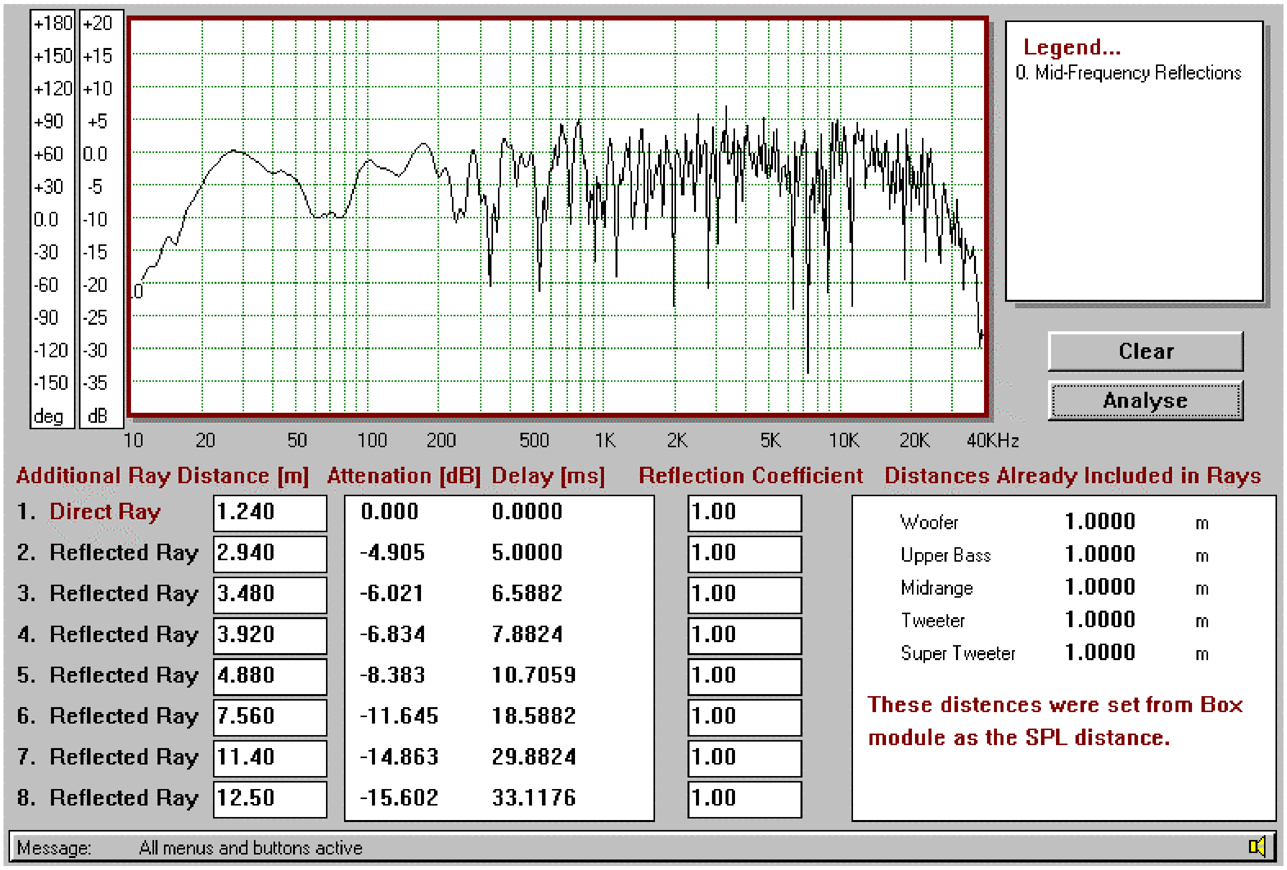
Figure 2. Adding two waves shifted by 10cm.

The 10 cm distance happens to be half of the wavelength (180 deg. shift) of 1700Hz sinewave. If we add two sinewaves of the same frequency and shifted 180 deg, the result should be total cancellation. Indeed, this is clearly depicted on Fig 2. The first null occurs at 1700Hz followed by a +6dB peak at 3400Hz. At 3.4kHz the 10cm distance is equivalent to 360 deg phase shift, so both waves combine constructively. Next, another null occurs at 5100Hz, as the phase shift over 10cm distance equals 360+180 deg (phase reversal) and so on.

Adding more rays.

Adding more paths, each one delayed by a different amount, produces effect depicted in Fig 3. In this example, we have 8 rays added together - one direct and seven delayed. All delayed paths are 100 % reflected, there is simply no absorption in the reflecting surfaces. The resulting frequency response is heavily distorted. Similar analysis can be performed for any location inside the listening room.

Are all the reflections necessarily bad ?. Imagine that you save some perfectly absorbing material placed on all room surfaces and there are no reflections whatsoever. This is basically the situation in the anechoic chamber - the room is acoustically "dead". Most people would discard such room for listening pleasure.



	Additional Ray Distance [m]	Attenuation [dB]	Delay [ms]	Reflection Coefficient
1. Direct Ray	1.240	0.000	0.0000	1.00
2. Reflected Ray	2.940	-4.905	5.0000	1.00
3. Reflected Ray	3.480	-6.021	6.5882	1.00
4. Reflected Ray	3.920	-6.834	7.8824	1.00
5. Reflected Ray	4.880	-8.383	10.7059	1.00
6. Reflected Ray	7.560	-11.645	18.5882	1.00
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8. Reflected Ray	12.50	-15.602	33.1176	1.00

Distances Already Included in Rays

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Upper Bass	1.0000	m
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Super Tweeter	1.0000	m

These distences were set from Box module as the SPL distance.

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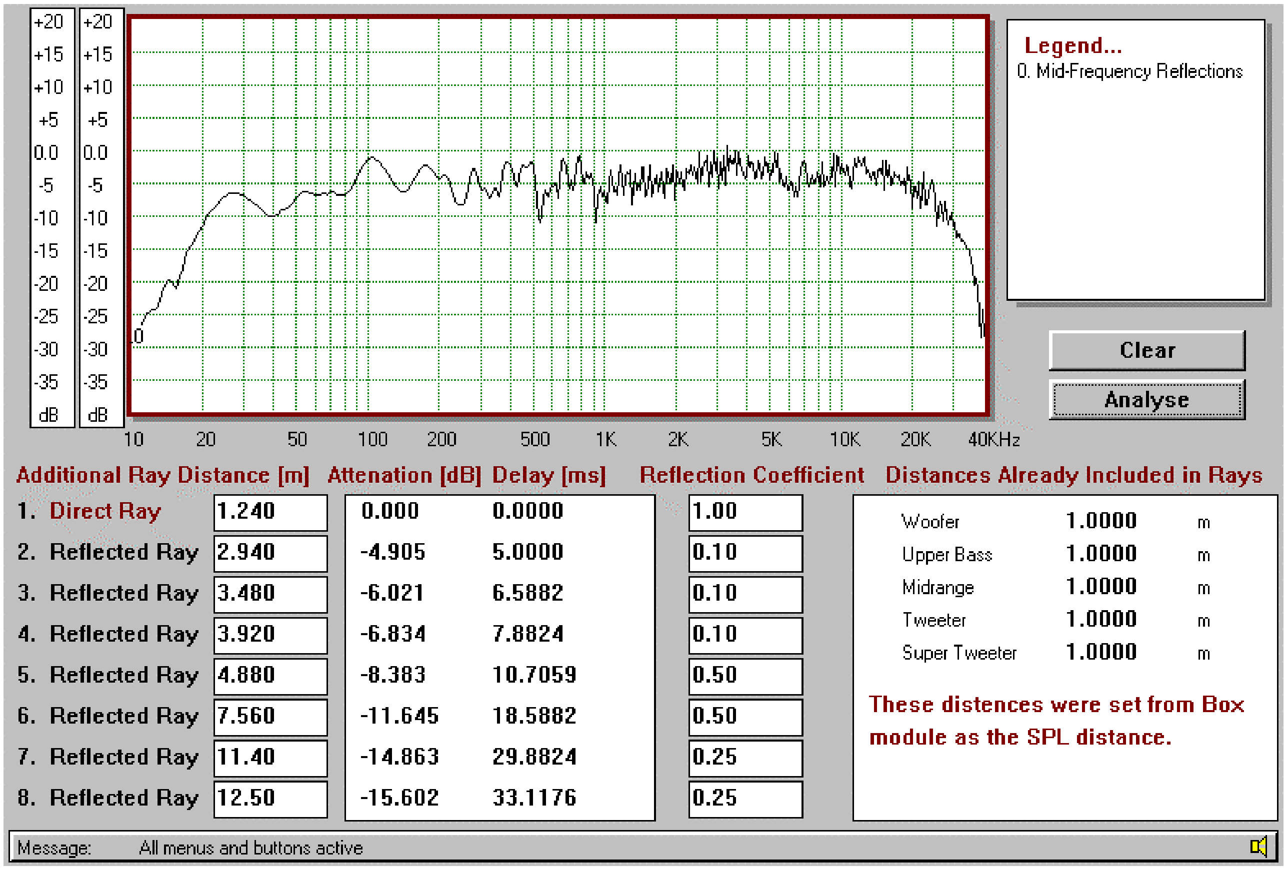
Figure 3. Adding 8 waves with different delays.

A solution seems to be somewhere in-between those two extremes. Most distortions of the curve depicted on Fig 3 are attributed to early reflections, which would still have sufficient amplitude to compete with the direct ray. These are the first bounce reflections from the loudspeakers off the nearest room surfaces to the listening positions. Therefore, these early reflections should be looked at first. You could determine the paths of the reflected rays using the graphical method discussed before. The reflection points are then covered with an absorbing rugs or acoustical tails - depending on the required absorption.

The next step is to look at the lateral reflections (reflections from the side walls). It is recognized, that lateral reflections contribute to the image of the sound stage and spaciousness. It is therefore desirable to keep the lateral reflections only partially absorbed by the reflecting surfaces. This situation is depicted in Fig 4, where three rays representing early reflections are 90% absorbed, two lateral reflections are 50% absorbed and the back wall reflections are 75% absorbed. Professional literature lists absorption coefficients for a number of common building and decorating materials, so I advise you to consult the books on this matter.

Absorption capability of the materials are heavily frequency dependent and are best in the mid- to high-frequency range. Porous materials, like foam and fiberglass, are very effective at mid and high frequencies, but loose efficiency at low-frequencies. Therefore the above model and discussion is only valid for frequencies above 300Hz.



	Additional Ray Distance [m]	Attenation [dB]	Delay [ms]	Reflection Coefficient
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4. Reflected Ray	3.920	-6.834	7.8824	0.10
5. Reflected Ray	4.880	-8.383	10.7059	0.50
6. Reflected Ray	7.560	-11.645	18.5882	0.50
7. Reflected Ray	11.40	-14.863	29.8824	0.25
8. Reflected Ray	12.50	-15.602	33.1176	0.25

Distances Already Included in Rays

Woofer	1.0000	m
Upper Bass	1.0000	m
Midrange	1.0000	m
Tweeter	1.0000	m
Super Tweeter	1.0000	m

These distences were set from Box module as the SPL distance.

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Figure 4. Adding 8 waves with different delays and reflection coefficients

Room modes.

Listening room acoustics at low end of the spectrum tends to be one big compromise, especially in small rooms. Standing waves are a fact of life in acoustically untreated rooms, and this will of course degrade the performance of a well designed loudspeaker system. Alternatively, stated in other words, installation of a loudspeaker system, capable of energizing lowest room modes, may well reveal that the room acoustics are less than perfect.

Room modes (natural resonant frequencies) occur across the entire frequency range. Professional treatment of the modes involves "bass traps" - typically a large absorbing element located in corners of the room. This idea may be readily applicable to a listening room in a recording studio, but for the rest of us, it may be difficult to get all members of the family to agree to it. If this is your situation, there are a few things you may need to consider to avoided basic mistakes when analyzing low-frequency issues of the home listening room.

Every room mode has associated acoustic pressure pattern with it. The pressure varies from 0 (null, no sound) to maximum (peak of the standing wave). When the music is played in the room, the modes are excited accordingly and the pressure pattern changes and shifts dramatically within the boundaries of the room.

Modes (all modes: axial, tangential and oblique) can be characterized by the following: (1) Bandwidth B - inversely proportional to the reverberation time: $B = 2.2/RT60$. Reverberation time depends on absorption, so the more absorption, the shorter the RT60 time and wider the mode bandwidth. (2) Decay - again, mode decay depends on the distribution of the absorbing material in the room and (3). Density - increases with frequency. Above 300 Hz room response smoothes markedly with frequency.

Let me now define the problem: you are the proud creator of a system capable of reproducing sound down to 20Hz, but when you sit down and listen to the sound, the low end around 20Hz is definitely missing. Assuming the problem is non-trivial, you are most likely sitting in the null of the pressure pattern for 20Hz mode. The importance of knowing your room modes and associated pressure distribution is now becoming clear.

Mathematically, if the room has a simple rectangular shape, an elegant formula can be used to determine room natural frequencies and some more work is required to determine pressure distribution. If the room has complex shape, the problem involves solving Helmholtz equation in 3-dimensions, looking for eigenvalues and eigenvectors. This process is handled very well by Finite Element Method (FEM) approach. If necessary, the FEM can be quite accurate. The accuracy depends on many factors and some of the them are: size of the element used, order of approximating functions. The compromise on the other side involves computer processing speed and memory requirements. I therefore decided to accept errors of less than 5%, understanding, that we deal here with an "approximate" method.

The FEM.

Before we proceed further, a few words of explanation on the FEM are needed. This concept has been around for several decades and lends itself particularly well to solving Helmholtz equation for complex volume shapes. Within a volume V, enclosed by a surface S, the pressure p must satisfy wave equation:

$$\nabla^2 p + (\frac{\omega^2}{c^2})p = 0$$

c=speed of sound, ω=frequency of vibrations. On the hard surface S, the normal velocity:

$$\partial p / \partial n = 0$$

The solution to the above problem, expressed by an equivalent variational principle is:

$$\delta \int_V \frac{1}{2}[(\nabla p)^2 - (\omega^2 / c^2)p^2]dV = 0$$

The volume in question is divided into a large number of smaller elements, each having several nodes. I concentrate on an 8-node (8-corner) “brick” element with linear shape functions approximating pressure distribution within the element. The bricks are placed together to approximate the required volume and shape of the room. The solution of the problem is expected to assign each node a pressure value for every room mode (eigenvalue). When shape functions of the element are introduced into the variational principle, the equation is reduced to matrix eigenvalue problem:

$$[K - \frac{\omega^2}{c^2} M]\{p\} = 0$$

K is the "stiffness" matrix, M is the "inertia" or mass matrix. Now the matrix equation can be solved by standard eigenproblem methods.

Generally, the user of an FEM program is dependent on the detailed knowledge about theories, algorithms and assumptions behind the program for the proper selection of models and algorithms. The FEM knowledge base is huge and readily available, however, the immediate question is: do you need to become an FEM expert if you only need to analyze your room acoustics once ?.
Please read on.

Analyzing FEM output

In general, the loudspeakers tend to activate those modal frequencies, which have partial or full maximum at this particular location. Conversely, room modes, that have null at the loudspeaker location can not be energized.

Because some absorption and transmission losses are always present in the room, the modes can not develop infinite pressure patterns and will always decay when the source of excitation is removed. However, as long as there are reflections in the closed volume of the room, the modes will be present.

Solution that is always recommended is to install bass traps. If the economical and astethic factors are on your side, the problem can be solved, or at least partially eradicated. Bass traps will greatly reduce reflections, thus preventing the standing waves phenomenon taking full effect and you will gain much more freedom in positioning the speakers. You simply kill the problem right where it starts. I have browsed the Internet for some help in this area and I can testify, that there are several companies offering good solutions to this problem. Room modes, that need to be looked at are typically located below 100 Hz, so you need to make sure, that bass traps you wish to implement are really efficient at such low frequencies.

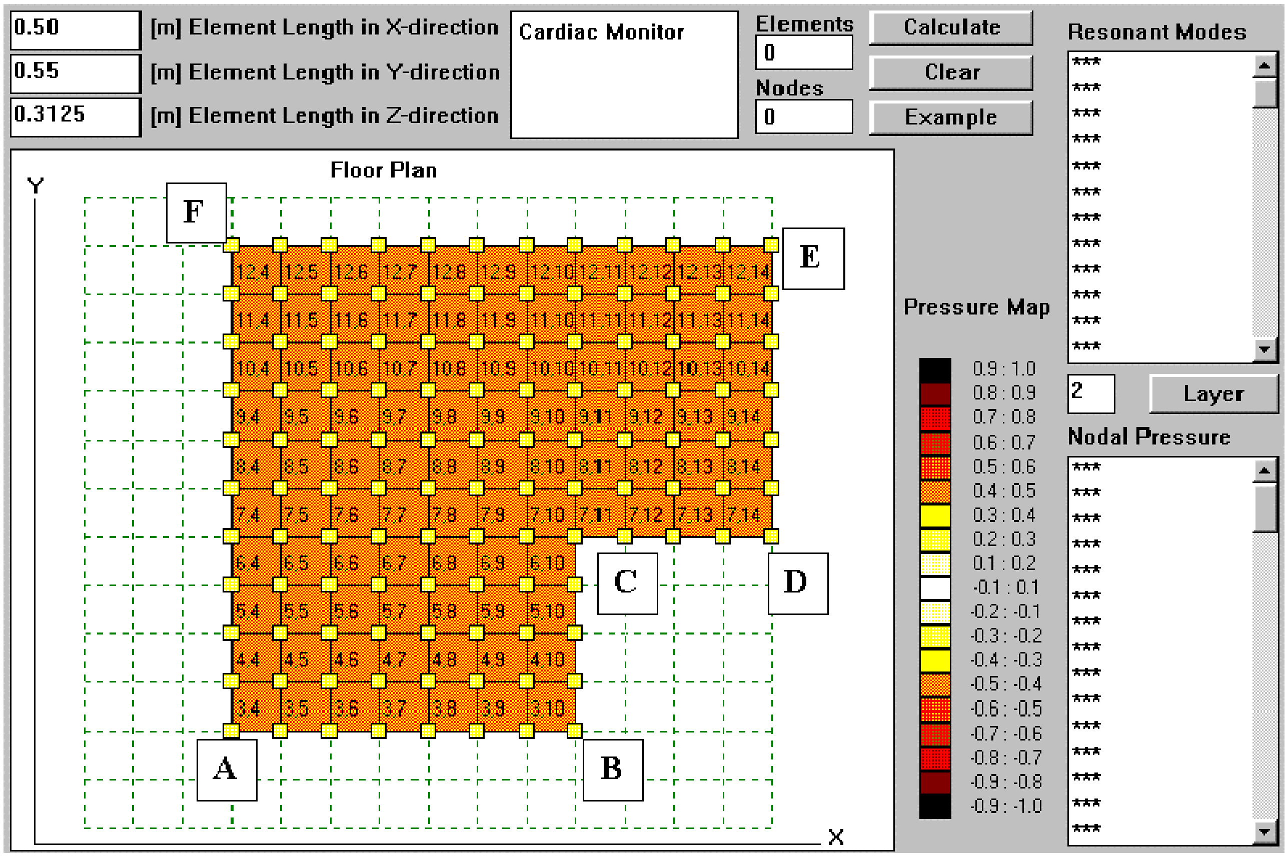
If, for whatever reasons, the bass traps are not an option for you I suggest careful review of the modal pressure plots. From this moment onward, I am not trying to solve the problem, but rather select the "lesser devil". Good FEM simulation software usually calculates all room modes and associated pressure patterns all at once, so when this lengthy process is completed you only need to flip through the list of modal frequencies to get the pressure pattern displayed on the screen. What you looking for is the location of pressure peaks and nulls for each mode (frequency).

Larger loudspeaker systems are typically made as floor standing and for purely asthetic reasons you will not place them in the middle of the room - but rather against the wall or even in the corner. From the pressure plots, you will notice, that pressure peaks also like walls and corners. Therefore, if you end up energizing room modes, you may as well energize as many of them as possible. If the room has many modes spaced evenly, the sound field tends to be smoother than in a room with only a few well separated modes. The latter room sounds boomy at those frequencies.

Next, the pressure plot analysis should reveal the locations of pressure nulls. This is essential, as one of the issues of prime importance here is to avoid cancellation of sound. Having located the nulls, you know at least, which areas of the room to avoid for quality listening. Many of us are would rather accept some amplification of sound than cancellation of sound (and our effort). Moreover, if this particular mode is too loud, you can always use electronic equalization to trim it down. The downside of living with the room modes is that the frequency response (loudspeaker + room) WILL be irregular. That is, if you avoid a pressure null at one frequency, you are likely to sit in a pressure null of another frequency. The problem here could be therefore stated in terms of: what frequency range is my favorite one, so I want to preserve it and which one I can sacrifice.

Listening Room example

For the purpose of further analysis, I selected a listening room having shape indicated in Fig 5. The floor plan is bounded by the A,B,C,D,E and F corners. The "brick element" I used to model the internal volume of the room has the following dimensions: X=0.5 meter, Y=0.55 meter and Z=0.3125meter.


0.50 [m] Element Length in X-direction

0.55 [m] Element Length in Y-direction

0.3125 [m] Element Length in Z-direction

Cardiac Monitor

Elements: 0

Nodes: 0

Layer: 2

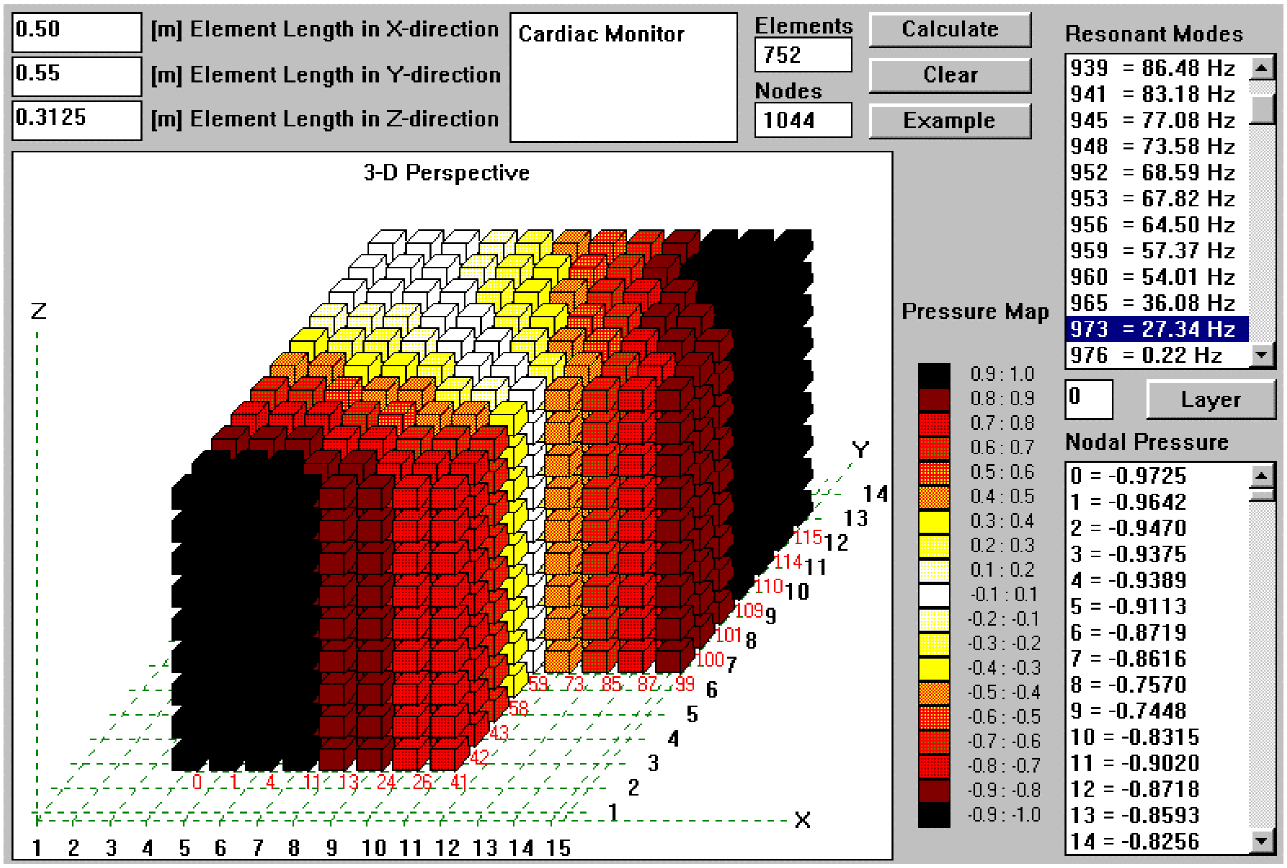
Figure 5. Listening room having shape.

The FEM tool I used calculated room modes and produced pressure distribution patterns shown in Figures 6-10. The colour coded pressure map was adjusted such a way, that on a black&white printer, the peaks of the pressure appear black and nulls of the pressure appear white.

Analysis

1. Fig 6 shows pressure distribution of the 27Hz (lowest) mode. It appears as a straight line between C-F corners.
2. Fig 7 shows pressure distribution of the 36Hz mode, which appears as gently curved line running from X=3,Y=7 to X=11,Y=13 coordinates.
3. Fig 8 shows pressure distribution of the 54Hz mode. The two curved lines running from the sides of the room indicate, the this is higher order mode.
4. Fig 9 shows 68.6Hz mode developed between the floor and ceiling
5. Fig 10 shows first order tangential mode of 73.6Hz developed between corners C-F and the ceiling.

As I mentioned before, higher modes, for this particular type and size of modeling elements, tend to attract small percentage error. You can reduce the error and increase overall accuracy by selecting elements of smaller size.



0.50 [m] Element Length in X-direction

0.55 [m] Element Length in Y-direction

0.3125 [m] Element Length in Z-direction

Cardiac Monitor

Elements 752

Nodes 1044

Resonant Modes

939 = 86.48 Hz
941 = 83.18 Hz
945 = 77.08 Hz
948 = 73.58 Hz
952 = 68.59 Hz
953 = 67.82 Hz
956 = 64.50 Hz
959 = 57.37 Hz
960 = 54.01 Hz
965 = 36.08 Hz
973 = 27.34 Hz
976 = 0.22 Hz

Layer 0

Nodal Pressure

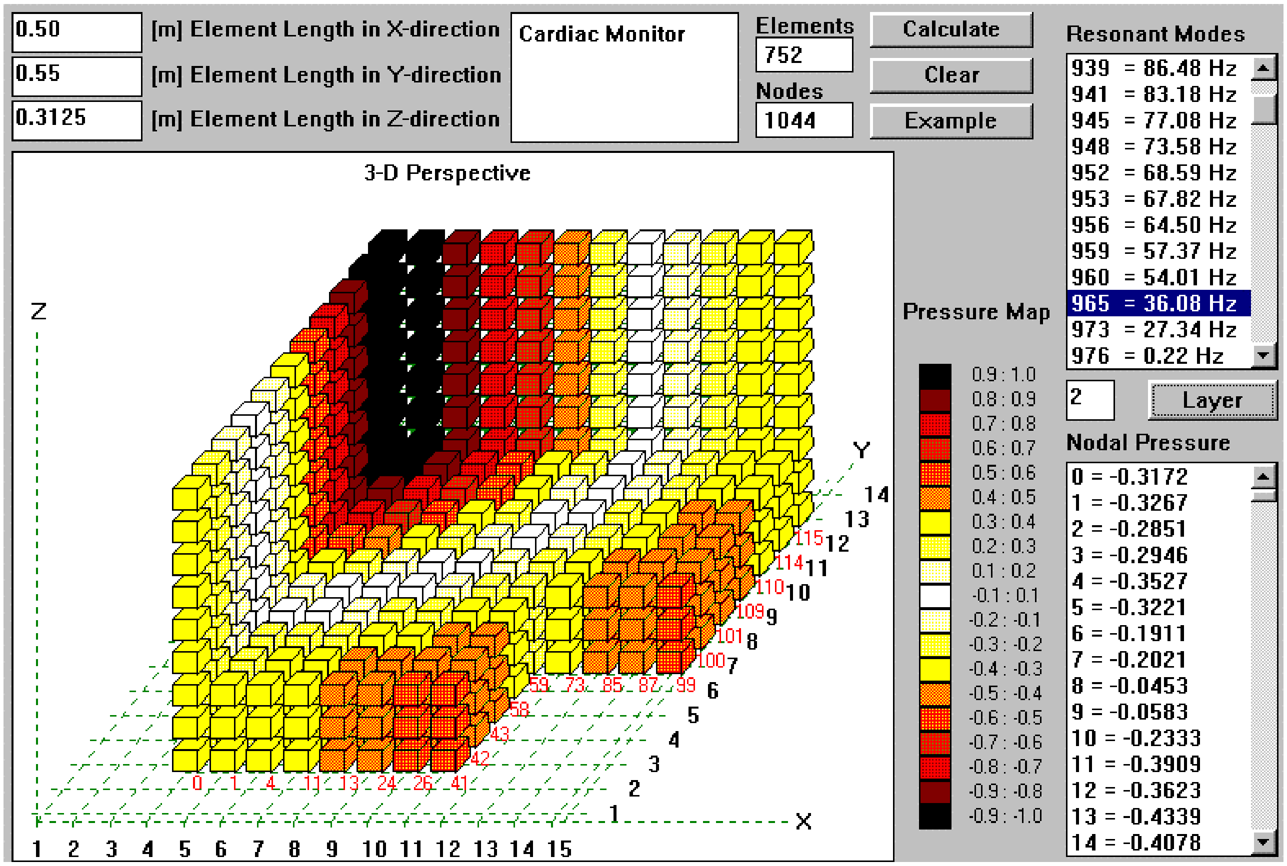
0 = -0.9725
1 = -0.9642
2 = -0.9470
3 = -0.9375
4 = -0.9389
5 = -0.9113
6 = -0.8719
7 = -0.8616
8 = -0.7570
9 = -0.7448
10 = -0.8315
11 = -0.9020
12 = -0.8718
13 = -0.8593
14 = -0.8256

Figure 6. Pressure distribution of the 27Hz (lowest) mode

For the given room dimensions, the lowest mode is 27Hz and it can only develop if you place the loudspeaker in corner E and select your listening position in corner A (see Fig 6). Area to avoid for listening position is the straight line between corners C-F. The second lowest mode is 36Hz (see Fig 7) and this one is not readily predicted without the FEM method. To energize this mode, I would place the second loudspeaker right in the F corner and avoid listening positions half-way along the walls F-E and A-F and also middle of the room.

Two things need to be emphasized strongly here: (1) by placing your loudspeakers in the corners of the room, you take advantage of what is known as “room gain”. It can add as much as 10dB at low end frequencies to your loudspeaker output, as compared with the “free space” response, (2) room modes, being based on standing waves phenomenon, also amplify the sound at specific frequencies. Therefore, you do not need to locate your listening position at nodes with 100% pressure. I would strongly suggest to aim for 40-60% pressure nodes locations but avoid nodes of 0% pressure at all costs.

With the above in mind, you will find, that placing the subwoofers in corners F and E and selecting you listening area framed by [X6,Y4], [X10,Y4], [X6,Y6], [X10,Y6] points secures reasonable (not perfect) reproduction of the lowest two modes. As you can see, I would recommend a satellite system with two subwoofers and two satellites, one located in corner F and the other, half-way along the F-E wall.


0.50 [m] Element Length in X-direction
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965 = 36.08 Hz
973 = 27.34 Hz
976 = 0.22 Hz

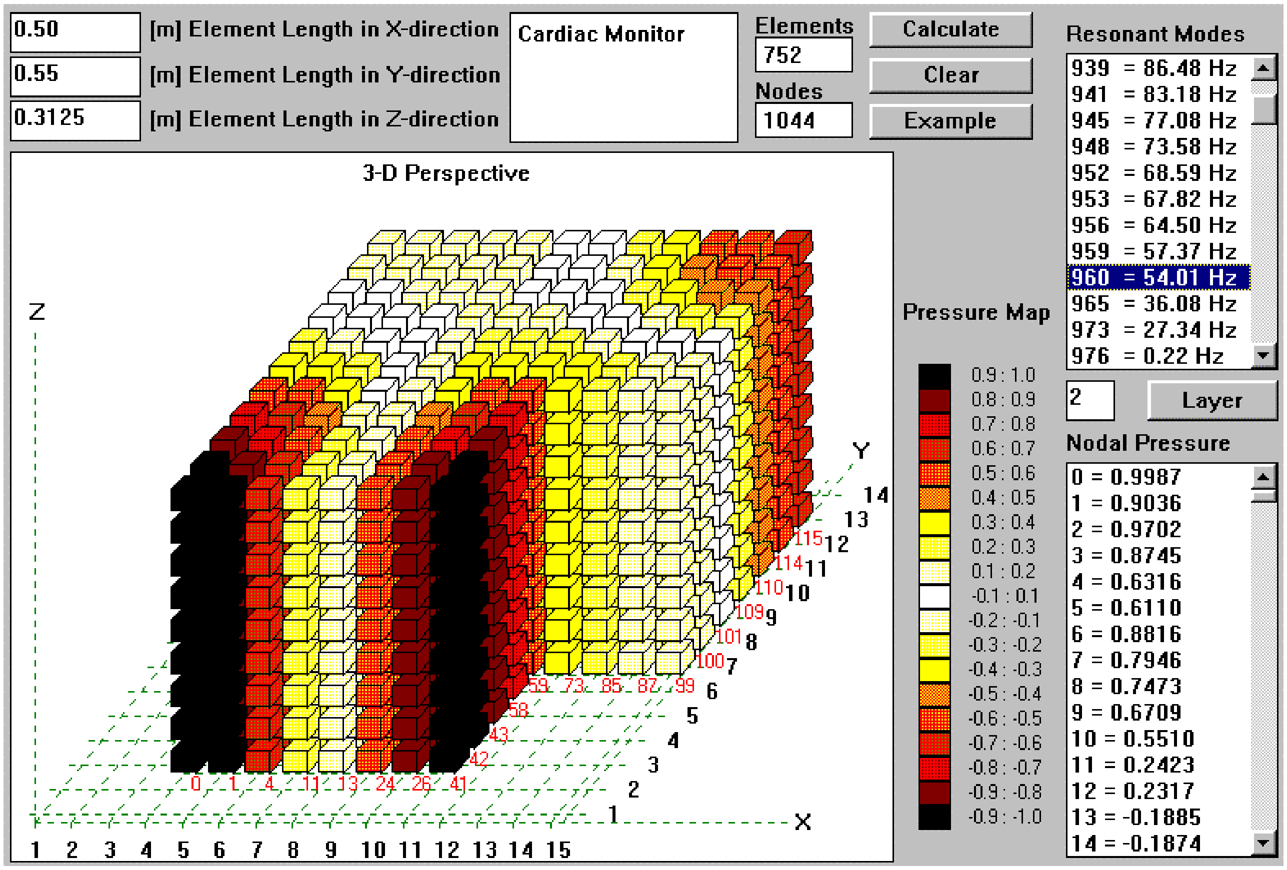
Layer 2

Nodal Pressure
0 = -0.3172
1 = -0.3267
2 = -0.2851
3 = -0.2946
4 = -0.3527
5 = -0.3221
6 = -0.1911
7 = -0.2021
8 = -0.0453
9 = -0.0583
10 = -0.2333
11 = -0.3909
12 = -0.3623
13 = -0.4339
14 = -0.4078

Figure 7. Pressure distribution of the 36Hz mode

Higher modes, shown on Figures 8,9 and 10 are useful in understanding what is the cost of this particular arrangement and I suggest you draw your own conclusions here.

Some of us will be tempted to take advantage of the room modes. Say, that you are interested above all in reproducing 20Hz wavelengths - because you purchased these special woofers and designed this unique enclosure and so on. In my opinion, this quite legitimate point of view. Today’s electric bass guitars have 5 strings and easily generate fundamental frequency of 20-30Hz. Special sound effects recorded on digital video discs are also rich in low frequencies too. If your thinking follows along these lines, you need to perform Modal Analysis of your listening room, determine pressure distribution pattern and only then, make an educated decision about your listening area. Having this out of the way, you can now use Ray-Tracing method to improve room’s performance at higher frequencies.


0.50 [m] Element Length in X-direction
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Cardiac Monitor

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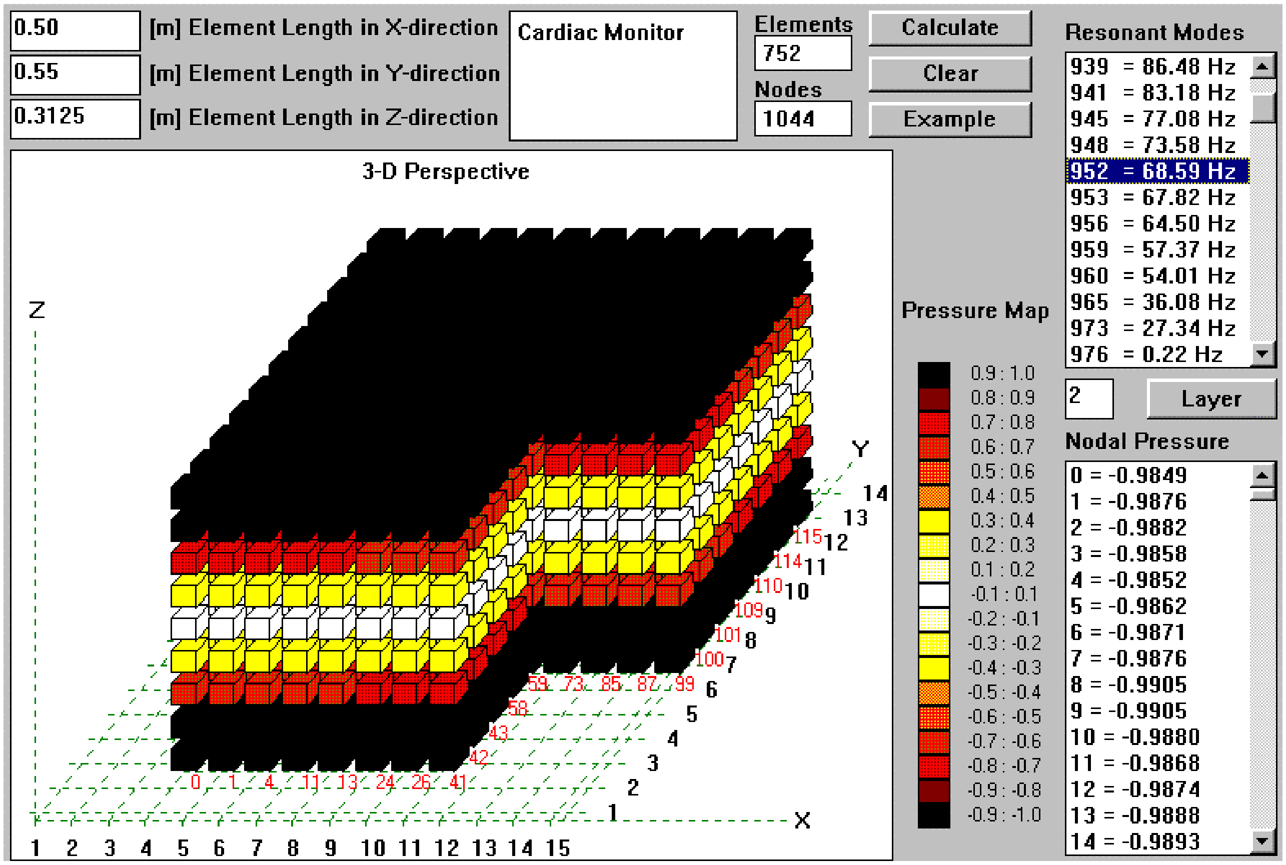
976 = 0.22 Hz

Layer 2

Nodal Pressure
0 = 0.9987
1 = 0.9036
2 = 0.9702
3 = 0.8745
4 = 0.6316
5 = 0.6110
6 = 0.8816
7 = 0.7946
8 = 0.7473
9 = 0.6709
10 = 0.5510
11 = 0.2423
12 = 0.2317
13 = -0.1885
14 = -0.1874

Figure 8. Pressure distribution of the 54Hz mode


0.50 [m] Element Length in X-direction
0.55 [m] Element Length in Y-direction
0.3125 [m] Element Length in Z-direction

Cardiac Monitor

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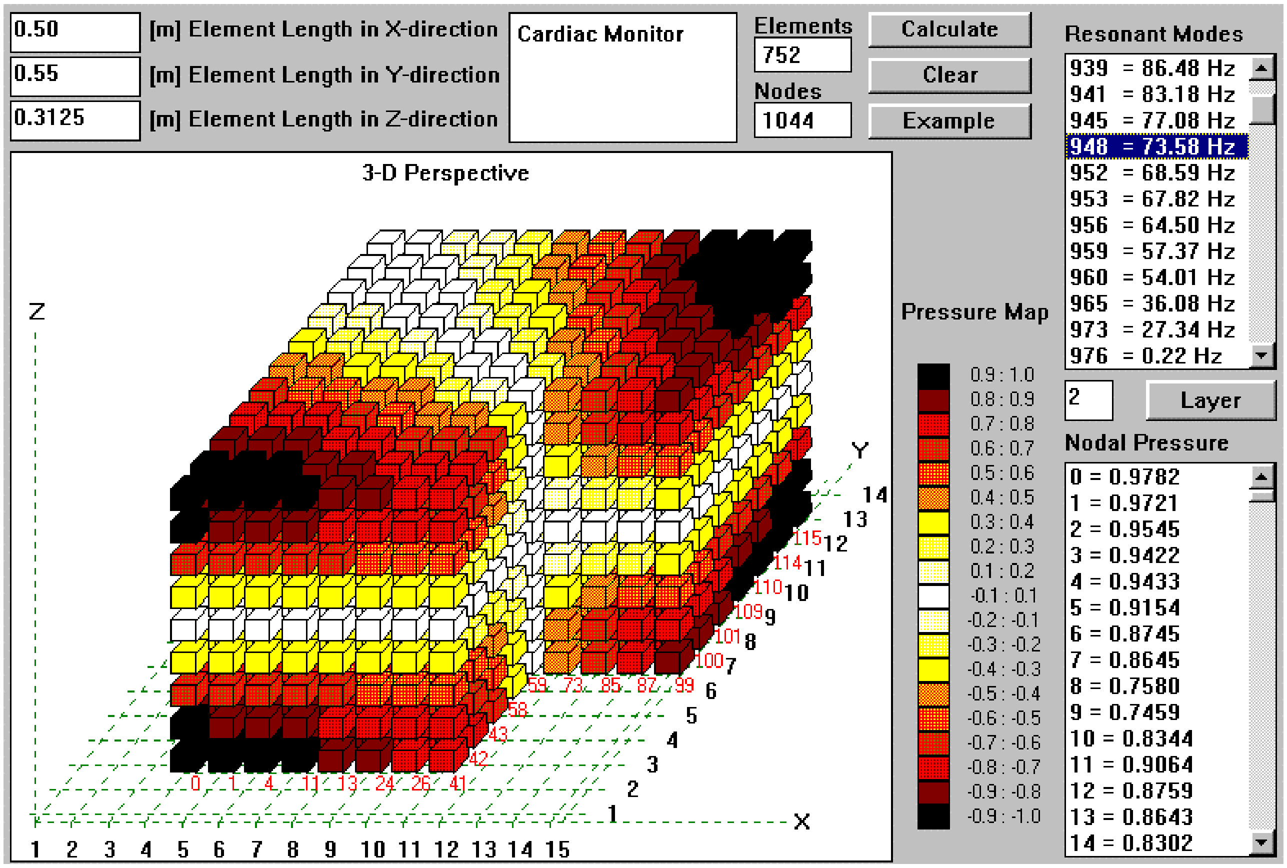
959 = 57.37 Hz
960 = 54.01 Hz
965 = 36.08 Hz
973 = 27.34 Hz
976 = 0.22 Hz

Layer 2

Nodal Pressure
0 = -0.9849
1 = -0.9876
2 = -0.9882
3 = -0.9858
4 = -0.9852
5 = -0.9862
6 = -0.9871
7 = -0.9876
8 = -0.9905
9 = -0.9905
10 = -0.9880
11 = -0.9868
12 = -0.9874
13 = -0.9888
14 = -0.9893

Figure 9. Pressure distribution of the 68Hz mode.



0.50 [m] Element Length in X-direction

0.55 [m] Element Length in Y-direction

0.3125 [m] Element Length in Z-direction

Cardiac Monitor

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956 = 64.50 Hz
959 = 57.37 Hz
960 = 54.01 Hz
965 = 36.08 Hz
973 = 27.34 Hz
976 = 0.22 Hz

2 Layer

Nodal Pressure

0 = 0.9782
1 = 0.9721
2 = 0.9545
3 = 0.9422
4 = 0.9433
5 = 0.9154
6 = 0.8745
7 = 0.8645
8 = 0.7580
9 = 0.7459
10 = 0.8344
11 = 0.9064
12 = 0.8759
13 = 0.8643
14 = 0.8302

Figure 10. Pressure distribution of the 73Hz mode.