Chapter 6. Enclosure Response to Rectangular Function.

Background

One of the most frequently cited criticisms of vented enclosures was their tendency to add mid-bass coloration to the reproduced sound. Early enclosures, particularly those which were misaligned, gained reputation for being "boom boxes". Even today, opinions concerning the subjective transient response of the reflex systems may be influenced by the boomy character of the many poorly designed examples still in production, of which some have Qtc values greater than 1.5. The fourth-order, 24 dB/oct final roll off for a reflex system endows it with a fundamentally poorer transient response that a sealed box. This particular characteristics inspired researchers to look for intermediate alignments and resulted in less-then-optimum efficiency alignments such as QB3. Generally speaking, the specifications of a loudspeaker system do not contain any requirements concerning the transient response. It nevertheless has to be mastered in certain conditions. A great majority of the systems will respond to a step function (rapid change in the supplied input voltage) with some ringing, evident in the transient response. The transient response here is defined as acoustic pressure in front of the box versus time after the step function was applied. So, how much ringing are you prepared to tolerate ?. Literature often advocates, that speaker systems should be matched to the type of music being reproduced. The rationale follows, that for classical music Qtc should be between 0.7 and 0.9 for the sealed system. This alignment is said to provide a refined and clean bass. Contemporary music lover would tolerate much higher levels of Qtc, perhaps as high as 1-1.5 (for sealed box). Some rock music fans like higher Qtc for sealed boxes, because it accentuates the bass (Qtc = 1.6-2.0). Different alignments will respond with different amplitude and duration of ringing. SoundEasy provides the designer with a time domain tool for plotting box response to a square-wave excitation. The frequency of the square-wave can be varied from 1.0 to 500.0 Hz and in the lower range of frequencies (1-10 Hz), the box response is identical to the transient response.

How It Is Done.

Passive loudspeaker system falls into a Linear Time-Invariant (LTI) category of systems. The nature of these systems could be studied using Difference Equations or, more appropriate for computer application, Discrete Fourier Analysis. SoundEasy takes advantage of the fact, that the frequency response function of the selected enclosure has already been formulated and can be used for process called 'Convolution'.

$$Vout(j\omega) = Vin(j\omega)*H(j\omega)$$

Convolution in time is reduced to a simple multiplication of complex functions; V() and H(). The first one, Vin() is the input square-wave transferred into the frequency domain using Fast Fourier Transform (1024-point Radix-2 FFT) algorithm. The second, H() is the frequency response of the simulated enclosure. The resulting function, Vout() is then acted upon using Inverse Fast Fourier Transform (1024-point IFFT) to obtain time plot of the system response. The block diagram of the process is shown in Fig 6.1 below.

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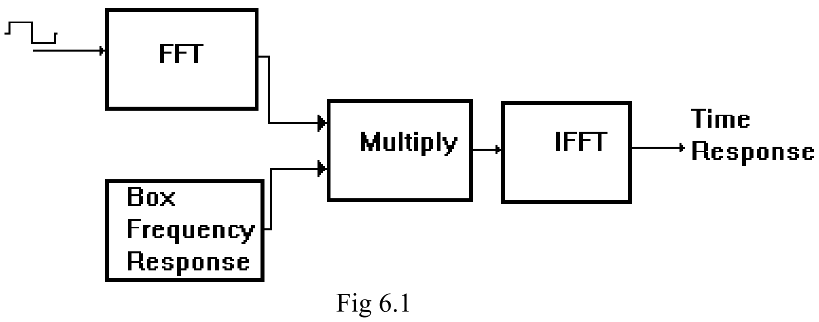

Fig 6.1

The input square-wave contains infinite number of odd harmonics. Amplitude of each harmonics is given below by the Fourier coefficient for odd and even values of 'n'.

Amplitude = 0 for n even, Amplitude = $\frac{4}{n*\pi}$ for n odd.

eg: Amplitude of F1 = 1.2732395 F2 = 0.0
F3 = 0.4244131 F4 = 0.0
F5 = 0.2546479 and so on.....

It is easy to observe, that only when all the harmonics are added with correct amplitudes and phases, the input waveform has the required rectangular shape. When the wave passes through the LTI system, the amplitude and phase of individual harmonics are changed. One can think of this process as generating 512 sinusoidal waves relating to each other with correct amplitude and phase (odd harmonics of the 1024 point FFT) and passing them all at once through the LTI system. In general, frequency response of a driver in a enclosure could be approximated as high-pass or band-pass filter. This implies amplitude and phase variations over the operating frequency range. As a result of this, some of the 512 sinusoidal waves passing through the LTI system will be affected to various degree. Some will be almost completely suppressed, others will be passed through, but shifted in phase and so on. The resulting waveform, Vout() will be again a linear combination (sum) of the 512 waves and may be vastly different from the square-wave entering the system. Transient response is much more difficult test for the loudspeaker system than a sine-wave sweep. The sine-wave sweep does not take into account phase shift of the system. Similarly difficult test, advocated by many audio reviewers is White Noise test, which contains infinite number of frequencies simultaneously present in the input signal, but their amplitudes and phases are random. Value of the Fourier coefficients indicates, that most of the wave's energy is present in the fundamental frequency F1 and several higher odd harmonics. For the low frequency transducer, it is vital to correctly recreate these frequencies. This way a solid and powerful sound can be generated.

Transient Analysis.

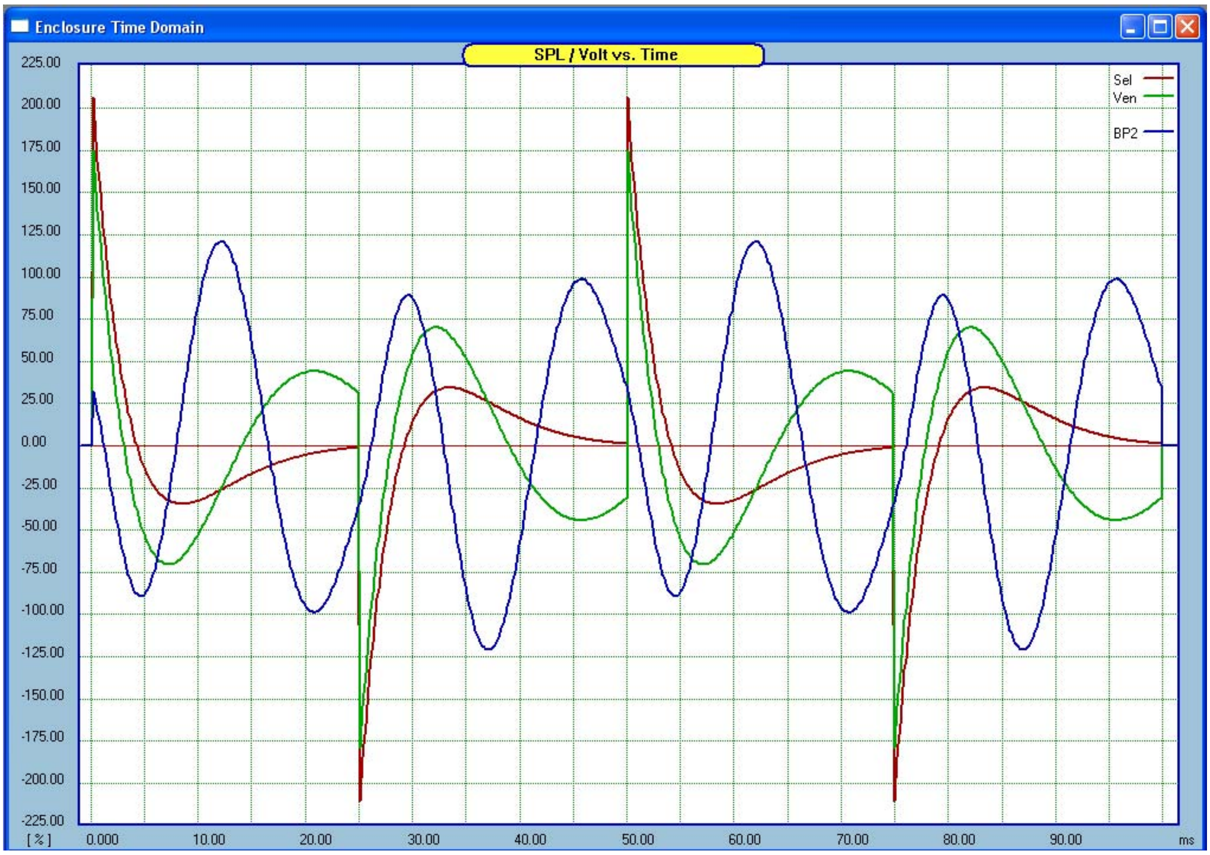

Fig 6.2 Transient response of sealed, vented and BP2 boxes

An interesting case is shown on Fig 6.2. The top section of shows frequency responses of the sealed, vented and band-pass2 enclosures. At the frequency of 50 Hz, the sine-wave sweep indicates 4dB difference between the responses, with the sealed box producing the least output, followed by the vented box and the BP2 producing the strongest output. However, when the sine-wave is replaced by the square-wave, the difference between the BP2 and other boxes becomes even more pronounced. The sealed and vented boxes clearly provide "differentiation" of the square-wave, while the BP2 box provides band-pass filtering. With the 50Hz frequency being the fundamental F1, the next odd harmonic in the square wave will be F3, at 150 Hz. This and all higher harmonics will be heavily suppressed by the BP2 enclosure and most of the wave's energy will be carried by the F1 fundamental frequency. The BP2 box offers the most energy despite passing only one (fundamental) harmonic.

The square-wave passed through the sealed and vented systems at the frequencies below F3dB system's cut-off frequency, will resemble a train of "spikes", with an initial overshoot and then gradual roll-off. If the frequency of the input square wave is still reduced, the system time response becomes transient response - see Fig 6.3. Here a 5 Hz square-wave is applied to the sealed and vented systems and the "classical" ringing can be observed. The amplitude and duration of the ringing can be now compared for all the designs. Fig 6.4 shows a sealed system with Qtc=1.5. The ringing is far too excessive for most kind of music. However, it would offer an impression of "more bass" to an untrained ear. Male voice would sound really unpleasant when listened to through this system. Fig 6.5 shows a misaligned vented system. Please note again the excessive ringing. Duration of the ripple can be read directly from the plot. Also, period of the ripple, converted to frequency (see Fig 6.5) should correspond to some peak on the frequency response. The top part of the Fig 6.5 shows a misaligned vented enclosure, which results in a pronounced peak on the frequency response around 50 Hz. To convert from period of the ripple to frequency, use the following formula:

1/(period in seconds) = (frequency of the peak in Hz)

Figure 6.3 Transient response of sealed and vented boxes at 5Hz

The time domain and frequency domain windows allow the user to **correlate enclosure responses in two domains**: **frequency and time.**

The example above illustrates well this dependency. Quite often, the response may be acceptable in the frequency domain, but will not be acceptable in the time domain. Eg; Enclosure may accentuate bass quite well (to the designer satisfaction) but excessive ringing, very disturbing on male voice, will cause the design to be modified. In order to perform time-domain analysis, please select “Time Domain” option from the “Tools”. Before you open the TD window, it suggested, that you reduce the vertical size of the main window. Simply shorten the main window from the bottom so that the 'Message' line is cut out of the visible area of the window. The reason for this is, that once you open the TD window and then click-on the main window to change some data, the main window will cover completely the TD window making it difficult to bring it back to front. If you shorten the main window before, the TD window is opened, you will have a small area of the TD window at the bottom of the screen to click-on and bring the TD window back to front. Plotting the time responses of the enclosure is achieved by (1) selecting the desired frequency of the square wave from the small editable window on the bottom of the TD screen, (2) activating the 'Plot' button to open a floating menu and (3) selecting the desired plot. Transient analysis becomes a very important factor when attempting to design loudspeaker system with active equalization.

In case of sealed boxes, a popular solution is to employ a peaked high-pass filter. However, some writers (V. Staggs, "Transient-Response Equalization of Sealed-Box Loudspeakers", JAES, December 1982) propose circuits with biquadratic transfer function. This solution is claimed to provide the desired equalization and improved transient response over the peaked high-pass filter. The peaked high-pass filter (2-nd order), together with the transfer function of the sealed box (also 2-nd order) would push the total order of the equalized system to 4. The solution proposed by Staggs, keeps the minimum order of the equalized system at the level of 3.

Modal Influence on Loudspeaker in Time Domain

It is often claimed, that for accurate sub-bass reproduction, you need a sealed enclosure. The word “accurate” is frequently used in reference to sealed enclosure time domain behavior. This excludes vented, passive radiator and acoustic bandpass woofers, because they all rely on resonant energy storage to increase efficiency and to reduce size. Indeed, the sealed enclosure only modifies already existing compliance of the driver, while vented enclosure adds air mass in the vent. This air mass, when combined with the air trapped inside the box, creates additional resonating circuit, or energy storage element, eventually affecting the sound quality produced by the loudspeaker system.

It is true, that sealed boxes do not add any additional “energy storage” elements over and above of what is already in the system. But have you ever stopped to consider, if there are perhaps any other “energy storage” elements involved in the reproduction of sound in your listening room?.

This question is not a trivial one, particularly, that your loudspeaker and you are placed in the same listening room. At the low-end of the audio spectrum (frequency less than 300Hz) the sound generated by your loudspeaker undergoes considerable changes in pressure and phase before it reaches your ears. The degree of the changes, commonly known as low-frequency room transfer function, can vary the sound in amplitude by more than +/-20dB. This variation of the room transfer function is due to room modes, or self-resonant frequencies. Please note, that we have just mentioned additional resonant frequencies. This automatically implies additional “energy storage” elements. Each room mode has associated with it its own ”energy storage” element, having its own resonant frequency and Q-factor.

To establish a reference point for a simple comparison, let us consider sealed and vented enclosures with reasonably well behaved frequency responses. The sealed box has usable volume of 70lt and the vented box is larger – 130lt. Both enclosures produce in free-field the “textbook” frequency domain responses, appropriate to their design – see Figure 6.4. The sealed box exhibits –12dB/oct roll-off and the vented enclosure has –24dB/oct roll-off at low end of the spectrum. Another thing immediately obvious, is the –3dB cut-off frequency, which would be around 30Hz for the vented enclosure and about 56Hz for the sealed box.

The analysis should not stop here. The loudspeakers will be eventually placed in the listening room so the effect of the listening environment must be taken into account when considering sound reproduction. In this article, we would like to focus on the transient response or time domain characteristics of the loudspeaker generating sound waves in an enclosed space. **We are very quick to take advantage of “room gain” effect on a subwoofer, but we are much less inclined to include room modes’ influence on the final sound produced by the subwoofer**. This attempt to highlight the issue is rather simple, but we hope to offer you one more angle to consider when attempting to decide upon the type of enclosure that would meet your complete set of expectations.

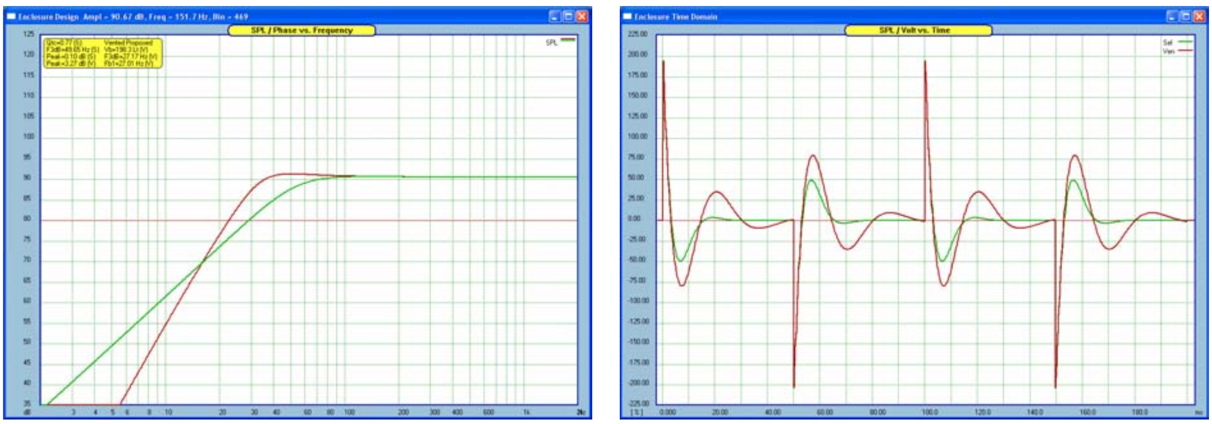

Figure 6.4 (a) SPL of sealed and vented enclosures. (b)Transient response of sealed and vented enclosures

Without any doubts, the decision is not a simple one. Just about every designer has slightly different set of preferences, so more often than not, the final design is a result of many compromises being made.

Time domain response to a rectangular pulse is also well defined for the above two enclosures. Figure 6.4b shows typical, free-field, time-domain response of vented (brown curve) and sealed (green curve) enclosures excited with 10Hz rectangular pulse. It is easy to notice, that sealed enclosure response has settling time of 15ms, while vented enclosure continues to ring till 50ms, which is more than 3-times as long. Also, the amplitude of the vented enclosure ripple around 8ms mark, is nearly twice (100%) as big as the sealed enclosure. Finally, the vented response crosses zero-line 4 times before it settles. We suppose, all the above would justify claims of superior performance of the sealed enclosure in time domain – known as having better transient response. The contribution of the "extra energy storage" element in the vented enclosure is quite evident from Figure 6.4. Those elements always tend to increase the amplitude of ripples and extend ringing time in the transient response of the enclosure.

Behavior of the sound waves in a small enclosure is a quite complex problem. However, the wave property of the sound energy makes it possible to introduce significantly simplified model of the problem, restricted to low frequencies, where only the room dimensions are of significance. In a rectangular room we are going to consider, the sound waves will be reflected and re-reflected between all 6 surfaces. When the reflections occur between opposite surfaces, the standing wave pattern generated this way is called "axial". Reflections involving four surfaces are called "tangential" and finally, reflections involving all six surfaces are called "oblique". The general, the room will exhibit an infinite number of modes.

The modes exhibit resonant character. They have natural resonant frequencies, bandwidths dependent on their damping factors, and amplification Q-factors also dependent on their individual damping. Modal density varies in frequency. Modes tend to be widely separated at lowest audio frequencies and then come closer together as the frequency of interest is increased. In addition, the effects of low frequency modes on the source frequency response are heavily dependent on the position of the source and receiver. For example: if a receiver is located in a pressure node, it will record no sound at all for a case of zero dumping factor for this particular node. In a typical listening room, exhibiting many modes, the frequency response of the source will be the vector summation of contributions of all modes, as well as the function of the source and receiver positions.

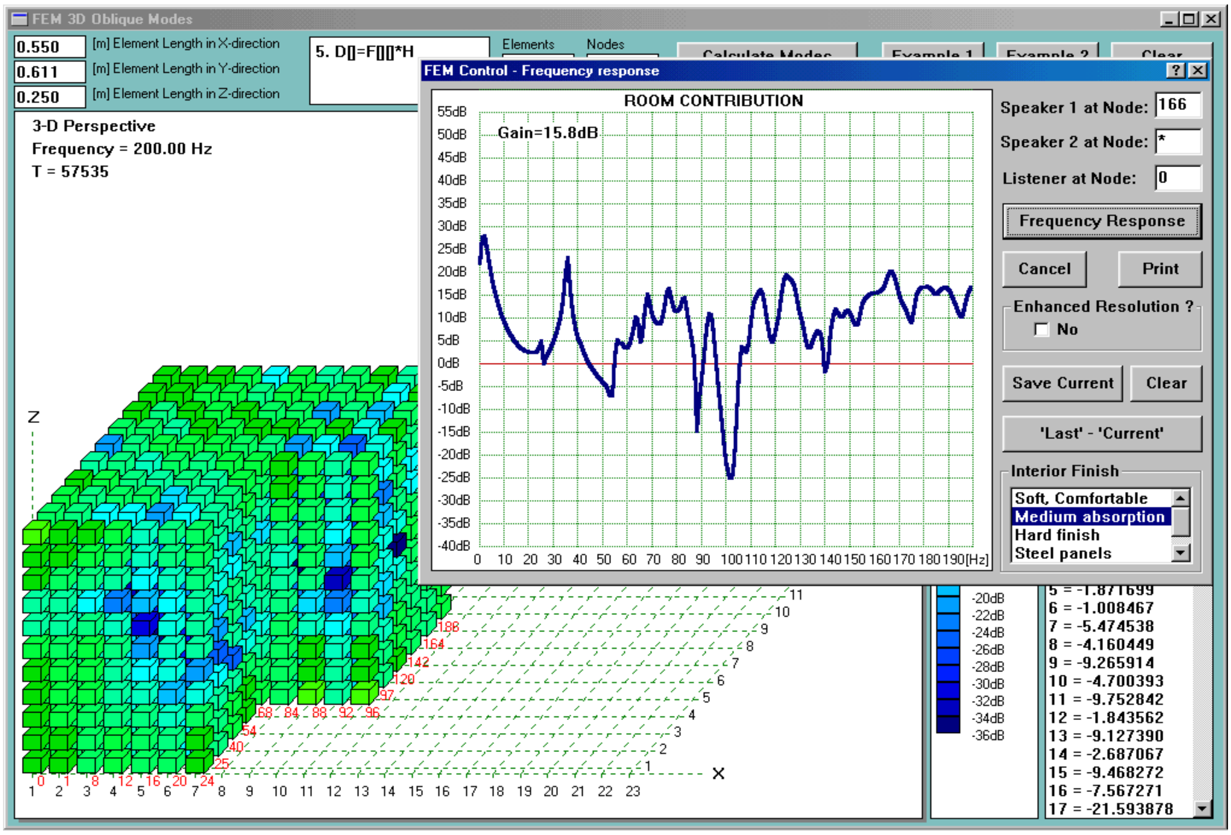

Figure 6.5. Example of a Room Transfer Function of L-Shaped Room

An example of an L-shaped room transfer function is shown on Figure 6.5 [2], where it is evident, that variation in SPL is large and there are many peaks and dips. The SPL variations are within +/-25dB and some modes have quite high Q-factor (eg: 36Hz mode).

In the following analysis of the two enclosures, we are trying to compare when placed in the room would be somewhat simpler, if we could limit the room transfer function to exhibit only 2-3 peaks. In order to create such room, we have devised an "electronic room", with only 3 peaks, using electronic circuit with three operational amplifiers. All we need to re-create room listening environment is the room transfer function, regardless of the way it was generated. we can therefore create some well defined electronic circuit and use it's transfer function as the simplified room transfer function. This approach allows me to control number of modes and their Q-factor quite easily.

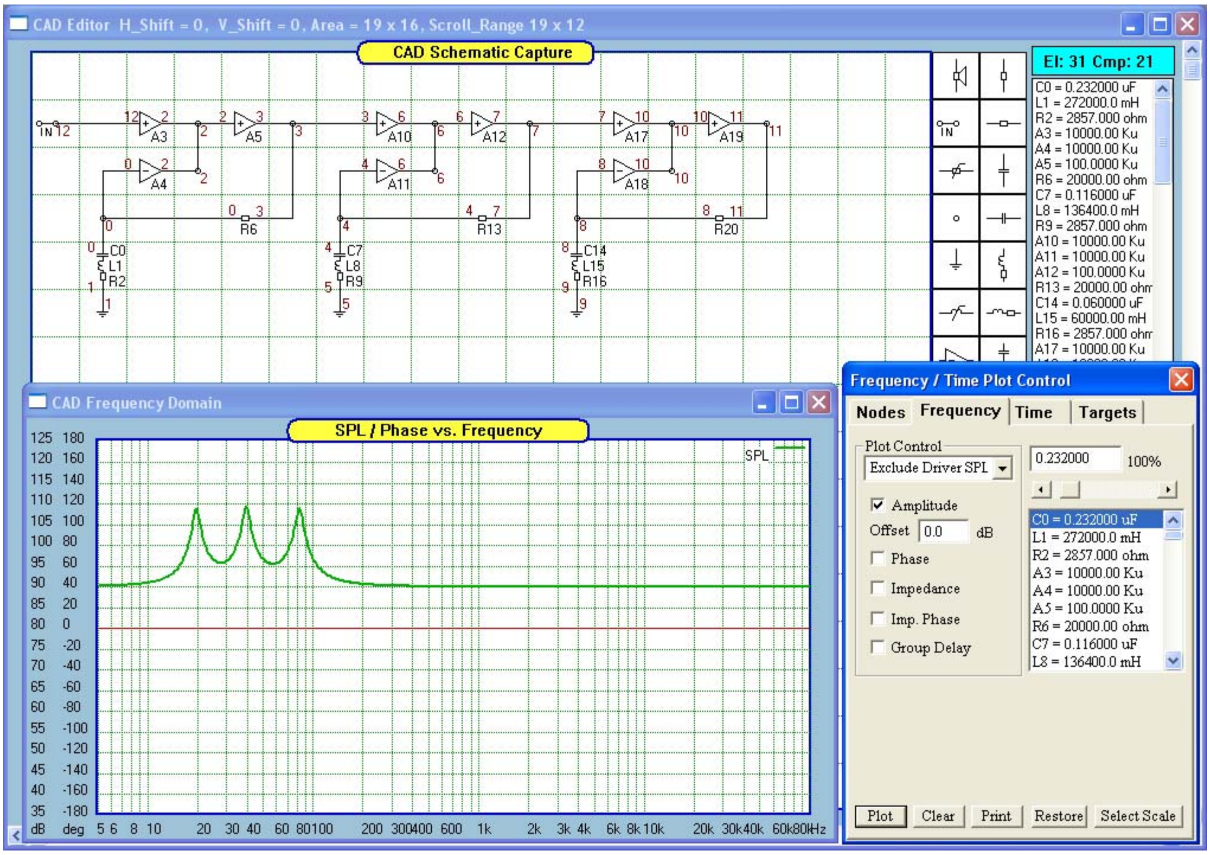

Figure 6.6 Simplified "room transfer function".

Our simplified room has only three modes at 20Hz, 40Hz and 80Hz. Each mode has Q-factor of 12 and corresponding gain of 8, therefore the humps created by the room will not add more than 18dB to the loudspeaker response. Also, we introduced only peaks, no dips, therefore we assumed no frequency band cancellation would occur. As you can see, our "electronic room" is much less severely affecting the sound than your typical listening room would.

Figure 6.6 shows the details of the electronic circuit we used to simulate our "electronic room". Basically, we have three differential amplifier stages, each having a series resonant circuit in the negative feedback loop. The loop is arranged such a way, that gain of each stage will be maximum at the resonant circuit center frequency. **The bottom section of the Figure 6.6 window shows the resulting frequency response – or room contribution.** The three modes are evident as the resonant peaks. It would be quite simple to add more peaks, or room modes to our "electronic room". All we would have to do, is to cascade more stages peaking at different frequencies. However, for the purpose of my simplified analysis, it is preferred to keep the picture as simple as possible, yet the ability to demonstrate the issues at hand must be clearly evident.

In the next step, we need to combine the "room contribution" with the two enclosures we selected for comparison. Mathematically, it is a simple multiplication of transfer functions, and the resulting combined speaker + room transfer function is shown on Figure 6.7. The drop in SPL towards the higher frequency end due the voice coil inductance, Le, in the model is removed.

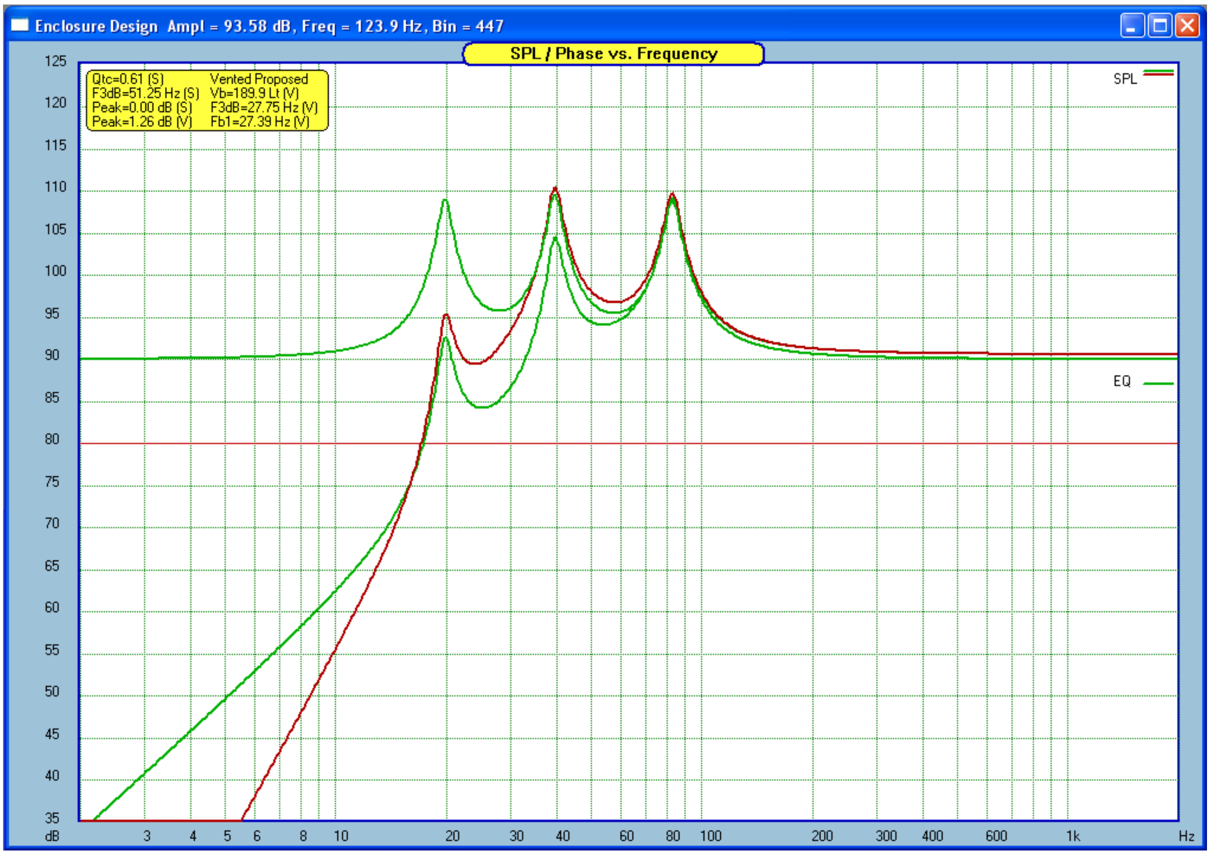

Figure 6.7. Room Transfer Function combined with both enclosures.

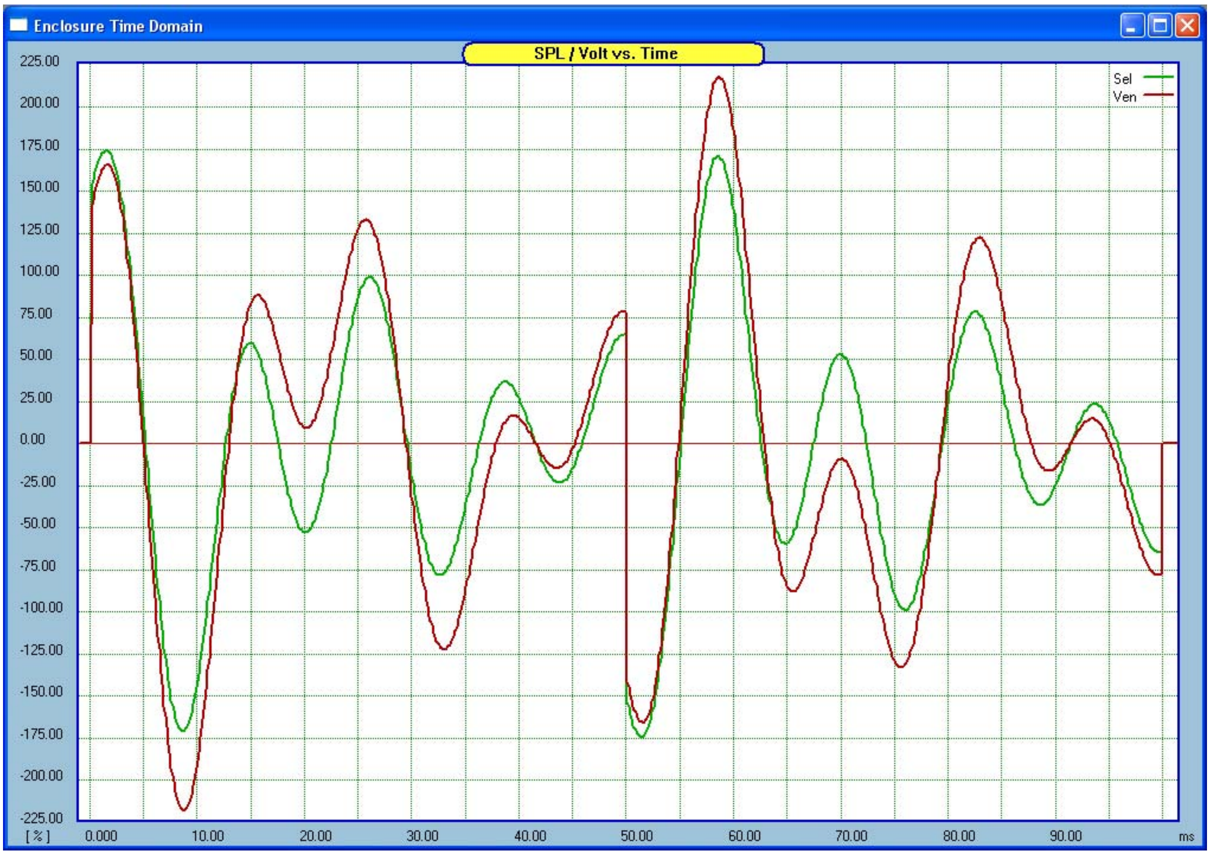

Figure 6.8. Transient response of sealed and vented boxes at 10Hz

Now, for the resulting time domain responses please review Figures 6.8 and 6.9. On Figure 6.8, sealed enclosure curve crosses zero line 8 times. Vented enclosure curve crosses zero line 4 times. Now, the vented enclosure ripple is only 30% higher than sealed enclosure. This is down from 100% for the anechoic chamber response. On Figure 6.9, vented enclosure has slightly larger ripple, but sealed enclosure has more pronounced 2-nd harmonic component. Total duration of ripples is comparable for the two enclosures.

At this stage, you would be forgiven for thinking, that the sealed box begins to look and sound awfully like the vented box. The sealed enclosure "accuracy advantage" now begins to disappear quite rapidly, even with only three simulated room modes. When we add more modes and also take into account dips due to phase cancellations within the room, we may expect the room characteristics to dominate the SPL and time domain responses even more. The actual number of room modes (or resonant storage elements) in your listening room is infinite. However, at higher frequencies they are so closely spaced, that it is impossible to separate individual modes any longer. This phenomenon actually works to your advantage, smoothing room response quite significantly.

We guess, it should be clear now, that the element responsible for this problem is the listening room itself. Please note, that both loudspeaker enclosures used for this simple comparison were relatively low-Q systems in comparison with the room modes Q-factors of 12. Therefore, you may expect, that it will be the room modes that will dominate the characteristics of the sound, rather than the type of enclosure being examined. **The saying "above 300Hz, you listen to the speaker, below 300Hz you listen to your room" begins to make more sense now.**

In general, it is quite a challenge to design high-SPL, low distortion subwoofer, capable of delivering 20Hz notes. The issue boils down to moving large volume of air. In case of a driver mounted in a sealed enclosure, the maximum SPL is clearly dependant on Xmax capability of the driver and this relates to BL non-linearity and suspension non-linearity.

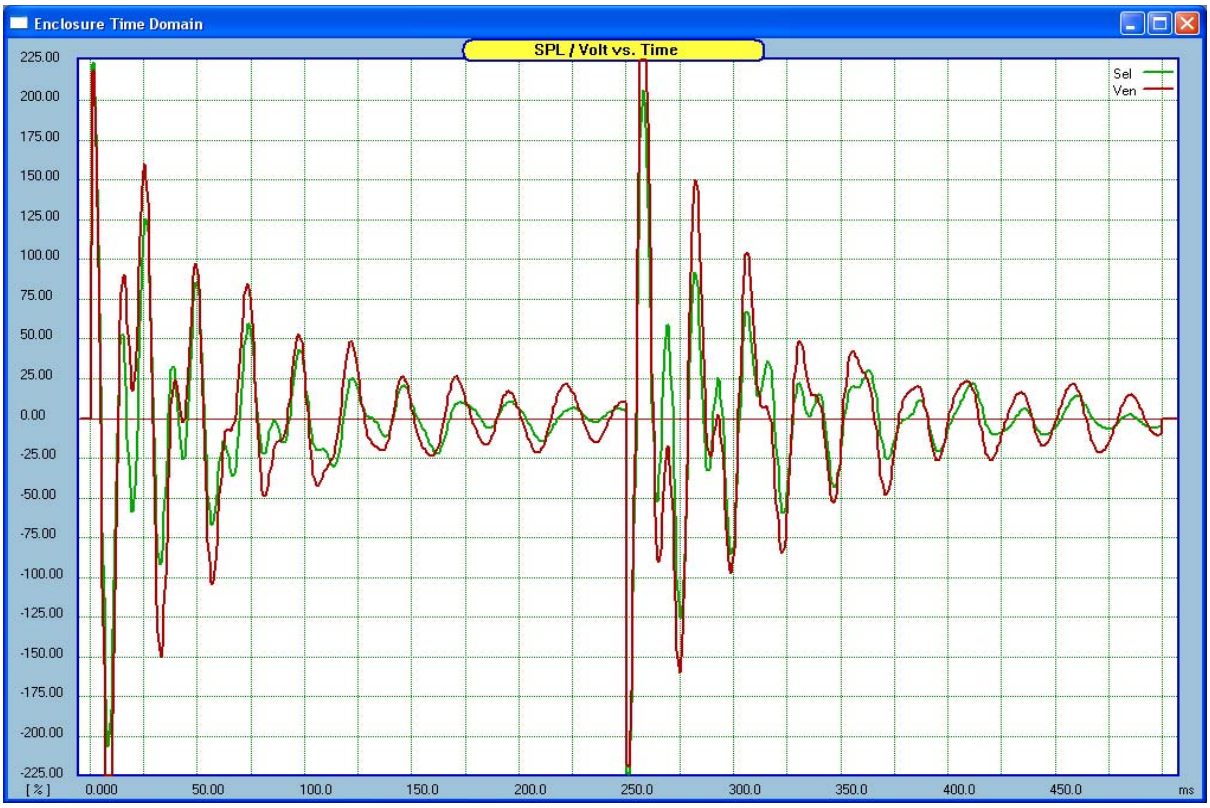

Figure 6.9. Transient response of sealed and vented boxes at 2Hz

Vented enclosure seems to have some advantage over the sealed box, because it actually reduces cone excursion around port resonance frequency. This can only work well, if the port itself is large enough and port compression and non-linearity problems are kept very low. The port takes over the job of generating the SPL, therefore reducing driver's motor system and suspension system linearity related problems. This in itself, would be worth taking into consideration when selecting appropriate enclosure for your subwoofer.

But there is more. Consider also the fact, that my vented enclosure actually produces 7.5dB more output at and around 30Hz than the sealed box. This represents more than four times (3dB +3dB) in required amplification power.

If you use electronic equalization, to raise the SPL of the sealed box at 30Hz or below, you will hit the Xmax much sooner, than you would with the vented enclosure, therefore at low end of the spectrum, you will never obtain the same SPL with the sealed enclosure as you would with the vented box.

As the final word, we would like to point you to a very interesting work of Soren Bech of Bang & Olufsen and Peter Bangs [1]. They have investigated the audibility of changes in the subwoofer lower cut-off frequency and slope. The slope was changed from 2-nd, 4-th and 6-th order and the cut-off frequency was varied between 20, 35 and 50Hz. Also, the influence of amplitude ripple and delay ripple was investigated. The results of the experiment showed, that the lower cut-off frequency has a significant influence on the perceived bass reproduction, while filter order was found not to be of significant importance. Also, amplitude ripples had a significant influence on the perceived bass reproduction, but the delay ripple had not.

If you dare to equate their filter slope with sealed and vented enclosures' slopes (sealed = 2-nd order and vented = 4-th order) and amplitude ripple with room modes gain (see Figure 5), you can draw parallel conclusions between the work of Beach and Bangs and the presentation above. In fact, the ear is quite sensitive to the amplitude ripples. Bucklien [3] found, that listeners have detected with 100% accuracy a 5dB peak (Q=10) at 85Hz. This would offer some indication as to why the room modes are so well imprinted in the sonic signature of your listening room.

References:

[1]. Bech S. and Bangs P.Quantification Of Subwoofer Requirements Part II, AES Preprint 5199, 109 Convention 2000 September, Los Angeles.
[2]. SoundEasy V4.00se manual. Chapter 15. Bodzio Software Pty. Ltd.
[3]. Bucklien R. "The audibility of frequency response irregularities" JAES 29, 1981.