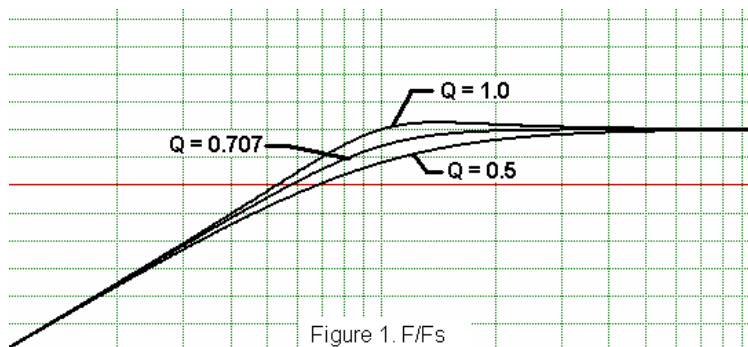


## About Sealed Box Q's

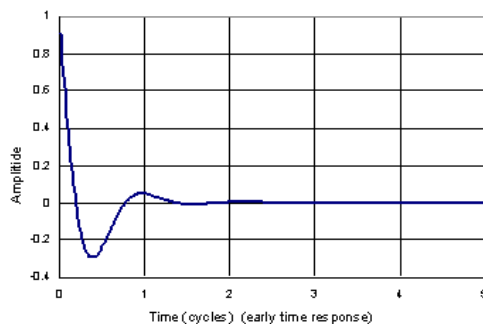
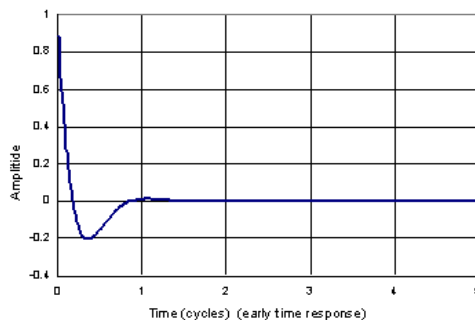
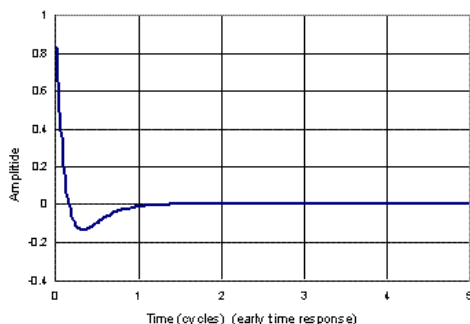
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The discussion of sealed box woofer systems often talks of the optimum  $Q_{tc}$  for the system. The transient response of the woofer system is frequently mentioned. For example,  $Q_{tc} = 0.5$  is critically damped,  $Q_{tc} = 0.707$ , the Butterworth alignment, yields maximally flat response,  $Q_{tc} = 1.0$  yields a 1.25 dB peak at 1.414 time the resonant frequency. Here I offer some thoughts on the roll of the system  $Q$ . You may find them controversial so feel free to disagree.

The first figure below shows the steady state, AC frequency response for each value of  $Q$ . The scale is 5dB/division with frequency normalized to the system resonance. The figures below the frequency response show the step response of systems with these three  $Q$ s; from top down,  $Q = 0.5$ , 0.707 and 1.0.



We see that there is indeed some difference between the responses in both the frequency and step response. However, how relevant are these differences to the sound of the system? Is this difference in step response the true cause of the differences in performance or are the differences somewhere else? The answer is both yes and no. Obviously the step and frequency response are uniquely related, but is the poorer step response directly the cause of boomy bass in a sealed system with  $Q = 1.0$  compared to  $Q = 0.5$ ? Is the small oscillation seen in the step response of the  $Q = 1.0$  system the direct cause of what may be perceived as loose bass?



To examine this we must look a little deeper into the operation of a woofer system. A woofer system is a forced system. That is, it responds to an input signal that is a continuously varying function of time. How does that relate to a step response? A step response is the response of a system to a signal that changes from one level to another instantaneously and then remains fixed at the new level. It is really the antithesis of a time continuous musical signal. So let us consider some other means of investigating how the woofer system really responds. Let us consider woofer systems with the same resonant frequency but with varying  $Q_{tc}$  and see how they respond to a signal that might better represent a musical input in the bass range. Assume our speaker system has a resonant frequency equal to low C on a stand up bass (around 30 Hz). What does a plucked bass note look like? Well, in its simplest form it is a very high  $Q$  resonance, as shown in Figure 5. Yes, there will be harmonics, but the fundamental will appear something like as is shown. So how does the woofer system respond to an electrical signal that would represent this input? Clearly the slight

difference in the decay of the step response of woofers with differing  $Q$  is insignificant compared to the many cycles of oscillation associated with the decay of the bass note. We next examine the first ten cycles of the response for our three different  $Q$  systems to the bass note more closely in Figures 6 through 8.

In these figures the red line is the input signal and the blue line is the woofer's output. Note that in all case the phase of the woofer's response is shifted by 90 degrees after a few cycles into the response. Thus we can't pin the boom on the phase response. If we concentrate on the amplitude of the woofer's response we see that the  $Q = 1.0$  is actually the most accurate. The phase is shifted, but the amplitude envelope (a line drawn through the peaks of the response) is identical to that of the input. By comparison the  $Q = 0.5$  and  $Q = 0.707$  woofers have an output envelope that is below that of the input signal. We would have to conclude that in the absence of other influences the  $Q = 1.0$  system has the most accurate response as it most accurately reproduces the input signal. When we consider that the bass note has many, many cycles and slowly decays to zero output, the extra, highly damped cycle or two in the step response is really an insignificant contribution to the response. ***In fact, for any reasonable  $Q$  the response is basically quasi-steady.*** That means the response is accurately represented by the steady state amplitude response with a slow decay. Since the decay of the applied signal is

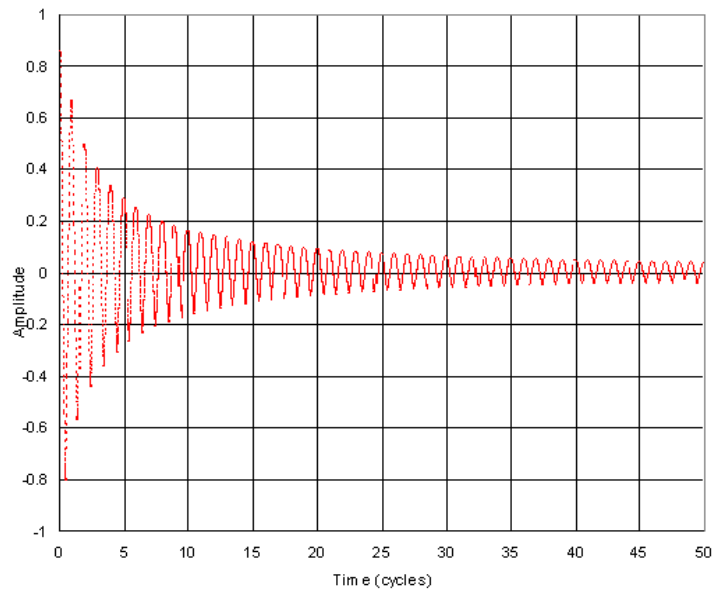


Figure 5. Modeled decay of plucked bass note.



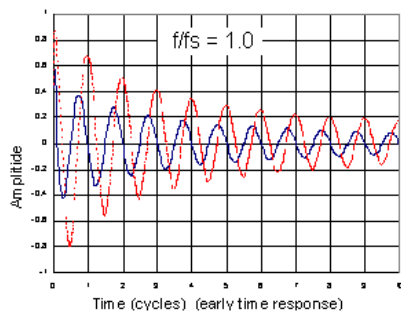


Figure 6. Comparison of system output (blue) with input (red) for  $Q = 0.5$ .

much longer than that associated with the woofer system's natural response to a step, the high pass nature of the woofer system and its  $Q$  have little impact on the forced output other than in its relation to the steady state frequency response. Thus with low  $Q$  woofers the fundamental is reproduced with lower and lower amplitude as  $Q\tau_c$  decreases. These low  $Q$  responses are often referred to as yielding tight bass. In fact, the bass is anemic. Referring to the first figure we see that for  $Q = 0.5$  for example, the fundamental is reproduced at an amplitude of -6dB relative to the input. The first harmonic would be only 2dB below the input and higher harmonics are reproduced at or very near the actually input level. As  $Q$  approaches 1.0 the fundamental and the harmonics are reproduced with more uniform relative amplitude.

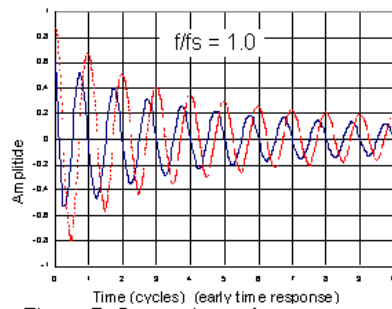


Figure 7. Comparison of system output (blue) with input (red) for  $Q = 0.7$ .

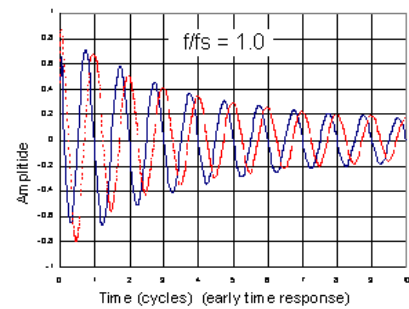


Figure 8. Comparison of system output (blue) with input (red) for  $Q = 1.0$ .

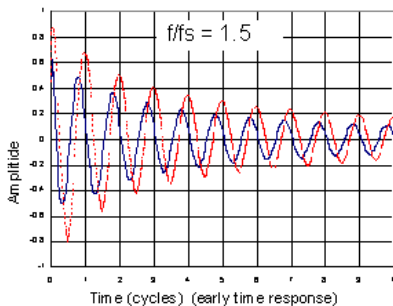


Figure 9. Comparison of system output (blue) with input (red) for  $Q = 0.5$ .

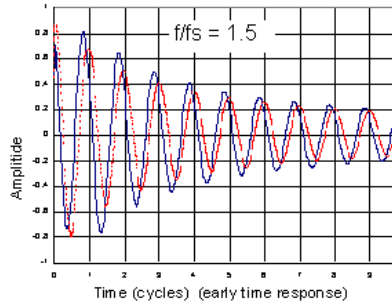


Figure 10. Comparison of system output (blue) to input (red) for  $Q = 1.0$ .

Since it was noted that the  $Q = 1.0$  system will have a 1.25dB peak in its frequency response  $\frac{1}{2}$  octave above  $f_s$ , we can look at the response at that frequency as well. Figures 9 and 10, to the right, show the response at a frequency of 1.5 times  $f_s$  for  $Q = 0.5$  and 1.0. We do notice that the  $Q = 1.0$  response exceeds the input amplitude slightly, however the  $Q = 0.5$  response is still well below the level of the input. Which is more accurate? Which sounds better? Will the response sound boomy? These questions can't be answered without considering one additional piece of the puzzle. This piece is the room. In a very large room or outdoors the effect of room gain is minimal and the environment does not influence the response, as shown in Figure 11. It should be clear that the  $Q = 1.0$  system should sound more natural in such an environment. However, if a sealed box woofer

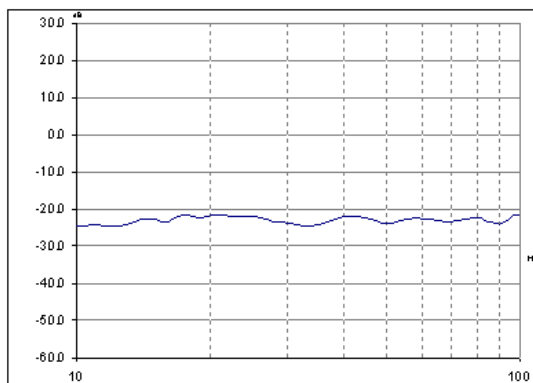


Figure 11. Room gain effect for a very large room.

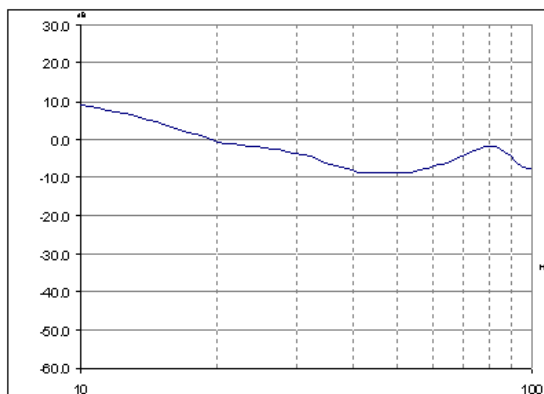


Figure 12. Room gain effect for a typical listen room.

system is placed in a relatively small, closed room, with room gain as depicted in Figure 12, the response below the fundamental room resonance will be augmented by room gain. If the room was perfectly sealed and the walls were perfectly rigid, the room gain would result in a 12dB/octave increase in SPL with decreasing frequency below the room's fundamental resonance. Coupled with a speaker of correct resonance and  $Q$  the resulting response would extend flat well below the speaker's and room's resonant frequency. However, if the speaker's resonance is below that of the rooms, then room gain effects can result in a blotted, boomy bass response. A low  $Q$  woofer system will help reduce this effect because of the greater roll off of the bass response from the woofer above it's resonance. There is clearly a need to consider the room size, woofer resonance and woofer  $Q$  when trying to achieve the smoothest, most extended bass response in a given room rather than building/buying a woofer simply because it has the lowest  $f_s$ . If  $f_s$  is well below the room resonance the room will be overloaded and the bass will almost certainly boom.

Just as correctly matching a speaker's  $F_s$  and  $Q$  to a given room is important when trying to get maximum bass extension, similar consideration must be given to applications where the intended speaker has a resonant frequency **well above** the room's resonance. In this case, room gain will not augment the initial roll off of the speaker. Thus, with small speakers it may be desirable to use a higher  $Q$  alignment to provide an overall flatter and more extended bass response. This generally yields a small speaker with a warmer, richer sound that actually sounds like a speaker of larger size with more extended bass response. The same speaker with a  $Q = 0.5$  will typically sound thin, bass shy and generally unpleasant though some may be convinced that since the woofer is "critically damped" the system is more accurate. Care must be taken not to over do it, however, as the response peak increases quickly as  $Q$  rises above 1.0

The point of this brief article is not to convince anyone that one value of  $Q$  is better than another. That is dependent on the application, as noted, and personal tastes. The point is a loudspeaker system's bass response is not so well defined by tests which reveal its natural response to a step change in input: the response of the system to an instantaneous disturbance from which the system then relaxes back to a rest state. Rather it must be realized that a loudspeaker system operates in a forced response mode. As such, what we hear at low frequency is typically dominated more by the system's steady state frequency response than its transient response to a step. This is because the electrical input signal forcing the driver's response is representative of the acoustic output of the instruments which were recorded, and will typically have decay rates which are much longer than that associated with woofer systems with  $Q$  of 1 or less.

In summary, when you hear a speaker that sounds boomy but is otherwise well designed

it is more likely not so much due to the overhang in the step response of the system. Rather it is because the particular woofer alignment ( $f_s$  and  $Q$ ) does not interact well with the local environment. When judicious choices are made in matching the speaker systems  $Q$  and resonant frequency with the room and intended use,  $Q$  values approaching 1.0 may provide a more satisfying and even more accurate reproduction of the input. Of course there are exceptions. Inexpensive speakers, poorly designed, may have  $Q$ s in significant excess of 1.0. However, even in those cases the boomy bass may have more to do with the peak in the steady state amplitude response around resonance rather than the poor system step response.

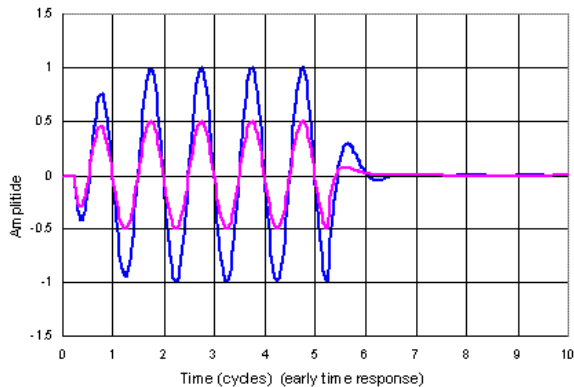


Figure 13. Response to a 5 cycle cosine burst at  $f_s$  for a  $Q = 0.5$  (pink) and  $Q = 1.0$  (blue) sealed box system.

#### Addendum:

The question has arisen as to the behavior of the sealed box system to a more rapidly decaying low frequency transient. While this can be gleaned from the impulse response, as stated above, where we see a slightly extended tail in the decay for a  $Q = 1.0$  system compared to a  $Q = 0.5$  system, it is perhaps clearer if the system response to a short burst is examined. Figure 13 shows the response of a  $Q = 0.5$  system (pink) and a  $Q = 1.0$  system (blue) to a cosine burst 5 cycles in length at the resonant frequency of the system. Since the signal is cut off abruptly this represents a worst case. What we see is that first of all the  $Q = 0.5$  system only achieves an amplitude of  $\frac{1}{2}$  input level. The  $Q = 1.0$  system achieved the full output level of 1.0. We also see that when the signal stops abruptly the  $Q = 0.5$  system overshoots slightly. The overshoot is about 18dB below the input level or about 12dB below the max output level achieved by the  $Q = 0.5$  system. The  $Q = 1.0$  system shows somewhat greater overshoot, about 10 dB below the input and the max output level the system achieved. The second wiggle seen in the  $Q = 1.0$  response, just after  $T = 6$ , is approximately 22 dB below the input level. Over all when evaluating the response to this short burst one would have to trade off the slightly longer tail of the  $Q = 1.0$  response compared to that of the  $Q = 0.5$  response against the failure of the  $Q = 0.5$  system to reproduce the burst with the appropriate level. Which is better? Again, that is dependent on the environment where the system is to be used.

I present the response of the  $Q = 0.5$  and  $Q = 1.0$  system to a shaped, 5 cycle burst at  $f_s$  in Figure 14. This may be a bit more realistic since the decay of the signal is controlled by the input, not the system's natural response after the signal is terminated. The red line is the input burst. Again, the interpretation is left to the reader, but the trade off is essentially an extra  $\frac{1}{2}$  cycle in the tail of the decay with much a much closer match in amplitude for the  $Q = 1.0$  system compared to the failure of the  $Q = 0.5$  system to approach the correct burst amplitude.

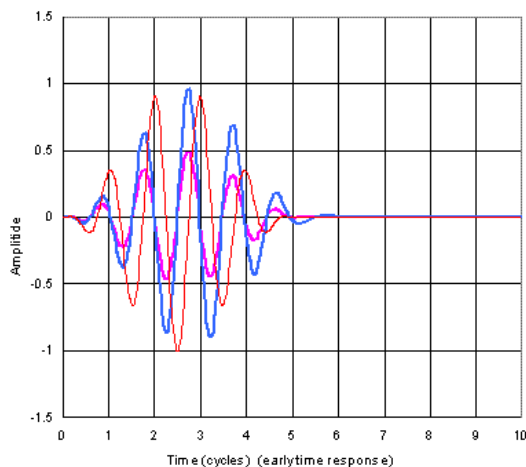


Figure 14. Response of  $Q = 0.5$  (pink) and  $Q = 1.0$  (blue) system to shaped burst response. Input shown in red

Finally I would like to touch on the ideal that proliferates many discussions: **Systems with  $Q = 0.5$  have the best transient response because they are critically damped.** I don't recall ever reading that in any engineering text book. What I do recall is the definition of a critically damped 2nd order system. For a low pass response the critically damped system, in response to a step, asymptotically approaches the step level from below, without overshooting, as fast as possible. If  $Q$  is greater than 0.5 the response will overshoot the step level and approach steady state via a damped oscillation about the step level. If  $Q$  is less than 0.5 the response will approach from below without overshoot but will take longer than the  $Q = 0.5$  system. For a high pass system, as a sealed box woofer, the  $Q = 0.5$  system will, as shown in figure 2, have a decay to the zero level which will undershoot and asymptotically approach zero from below without additional overshoot. If  $Q$  is greater than 0.5, as shown in Figures 3 and 4, the response will undershoot and then approach the zero level via a damped oscillation about zero. If  $Q$  is less than 0.5, the response will actually pass through the zero level more quickly than the  $Q = 0.5$  system with less undershoot and like the  $Q = 0.5$  system will approach the zero level from below without oscillation, but will take longer to return to the zero level. So

which system has the best transient response? How can that be answered without consideration of the intended application? If, as with a loudspeaker system, the intended application is for the system to follow an input signal as faithfully as possible, a forced response, then clearly the only way to evaluate the system is by consideration of its response to signals which are hopefully representative of the type of input signals which are applied to the system in use with, once again, consideration of the expected environment in which the system will be used.

There really isn't anything new presented here. I have made this presentation primarily because I sense there is a failure of many to recognize the relation between frequency and transient response and a blind belief that  $Q = 0.5$  systems are better because they are critically damped along with a failure to recognize the importance of room interaction with sealed box systems in relation to their cut off frequency. The intended purpose is to stimulate thought before building a system and to try and present a collection of different ways of looking at the system responses.

But wait, there's more. What happens if the input signal contains more than a single frequency component?



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