Eminent Technology TRW-17 Subwoofer

Part I: The Only Subwoofer

I could tell you that the new TRW subwoofer from Eminent Technology is better than other subwoofers, and I'd be right. For the TRW does go far lower in bass frequency than other subwoofers, and does play bass much louder than other subwoofers, and does play bass with much better accuracy, quality, dynamic impact, and transient response than other subwoofers. I could even therefore tell you that the new TRW is the best subwoofer, and I'd be right.

But it would still be misleading for me to tell you simply that the TRW is better than other subwoofers, or is the best subwoofer, for I would not be telling you the whole truth.

The whole truth, the scientific, objective truth, is that the new Eminent Technology TRW is the ONLY subwoofer.

That's a bold assertion. How do we justify it?

You see, saying simply that the TRW is better than other subwoofers, or is the best subwoofer, implies that the TRW is just another subwoofer, and is merely bigger, better, badder than other subwoofers, i.e. that the TRW is different from other subwoofers merely as a matter of degree. And, admittedly, if we were to look simply at matters of degree, the TRW is indeed better and the best, in all the bass parameters that matter: deeper bass extension, louder quantity of bass, more accurate quality of bass, etc.

But the TRW is not merely different from other subwoofers in degree. It is also different in kind. The TRW employs a wholly different, radical new subwoofer technology. So its bass performance is also wholly different in kind from other subwoofers, not merely of the same kind and better as a matter of degree.

So the more complete truth is that the TRW is a whole new animal, a whole new kind of subwoofer. But even telling you simply this would still be misleading. It implies that the TRW merely uses an alternative type of technology, with which conventional subwoofer technology might still be competitive.

The real truth, the whole truth, goes even beyond this. The TRW does not represent just another alternative subwoofer technology. The TRW is not merely different in kind from other subwoofers. Instead, the TRW is virtually the opposite in kind from other subwoofers. In most crucial conceptual aspects, design principles, engineering parameters, and strengths vs. weaknesses, the TRW is virtually the contrary of conventional subwoofer technology and of all other subwoofers. Now, since wherever there are two contraries, then one at most can be right, and since the TRW is demonstrably very right, it logically follows that all other subwoofers, being contrary, must be very wrong.

The other subwoofers are so wrong, in the contrary design principles they employ for trying to reproduce bass, that they are not really true subwoofers. These other subwoofers, as you will see by the end of this article's technical analysis, are merely pretenders to the throne. The only true subwoofer is the TRW. So the whole truth, the only truth that does not mislead you, is that the TRW is the ONLY subwoofer.

Let's take some brief looks at several concrete examples of what we mean by this opposite behavior, so you can better understand why the TRW is the only subwoofer.

A. Opposites in Radiating Area Behavior, and Coupling to Air

In order to make sound at bass frequencies, a driver must couple effectively to the air, so it can move the air. In order to couple effectively, it must have a large radiating area for bass frequencies. And, as the bass frequency to be reproduced goes lower (and the bass wavelength gets consequently bigger), the driver's radiating area must increase, if the driver is to retain its good coupling to the air for lower bass frequencies.

Conventional subwoofers fail miserably at achieving this crucial coupling. First, they are crippled by a radiating area that is too small. Furthermore (and the key point here), their cone drivers inherently all have an obvious intrinsic property: the radiating area of the cone stays constant at low frequencies, so the radiating area fails to increase as the bass frequency goes lower. Thus, the coupling effectiveness to the air plummets drastically for conventional subwoofers, for lower bass frequencies. A large conventional subwoofer woofer driver might be OK down to say 40 Hz, but below that it simply cannot couple effectively to the air, so it intrinsically cannot be a good subwoofer.

The TRW subwoofer is just the opposite. We saw that the cone drivers of conventional subwoofers inherently have the intrinsic property of a constant radiating area that fails to increase at lower bass frequencies, thereby making the coupling effectiveness plummet drastically for all conventional subwoofers. The TRW has the opposite intrinsic property. Its radiating area is not constant with frequency. Instead, the effective radiating area of the TRW inherently does increase, as the bass frequency to be reproduced goes lower. That's what should happen, for a true subwoofer to better retain its effectiveness in coupling to the air -- its ability to drive the air -- at the very low bass frequencies where true subwoofers are supposed to be able to do their job, and do their job well.

Indeed, the TRW's inherent property of increasing its radiating area at lower frequencies is so impressive that its effective radiating area intrinsically and effortlessly increases enough to actually approach infinity (!!), as the frequency being reproduced approaches DC.

All this is just the opposite of what we just saw in conventional subwoofers. Conventional subwoofer drivers do not change their radiating area for lower frequencies, so their coupling to the air they must drive plummets drastically at lower bass frequencies. The TRW does change its radiating area with frequency, progressively increasing it as the frequency to be reproduced goes lower, so its coupling to the air stays much better at low bass frequencies than the plummeting coupling of conventional subwoofers. It is the TRW that is behaving closer to how an ideal subwoofer should, while it is the contrary behavior of conventional subwoofers that is wrong, for reproducing low bass.

So, which of these opposites would you rather have as a subwoofer? Which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

B. Opposites in Reactance

Consider next reactance, as another example of opposite behavior. Conventional subwoofers have large reactance, plus severe reactance changes, at low frequencies. This reactance comes from the driver's free air resonance, compounded by the resonance of the enclosure volume with this driver, compounded by the resonance of the port or vent (if any). This reactance creates four huge sonic problems, which preclude correct bass reproduction. First, this reactance sets up a barrier fence at a certain frequency, below which the conventional subwoofer cannot go, to reproduce the full bass spectrum. Second, this reactance stores energy and then releases it much later in time (as bass overhang and ringing). This spurious delayed energy release not only creates a phony bass sound (boomy overhang), but also obscures subsequent musical information (of all frequencies) that happens to occur immediately after each bass transient. Third, this reactance robs energy from the initial bass transient (the energy contained in that delayed energy release has to be stolen from somewhere), so the initial attack of bass transients lacks sufficient dynamic impact. Fourth, this reactance grossly corrupts the time domain waveform put out by the conventional subwoofer, so that its contribution to the overall musical transient does not properly add up with and cohere with the waveform put out by the main loudspeaker for this same musical transient.

But again the new TRW subwoofer is just the opposite, of conventional subwoofers. It does not have any reactance at very low frequencies. Thus, the TRW subwoofer does not evince any of these sonic problems that reactance causes in conventional subwoofers. First, the TRW does not have any barrier fence precluding response to very low frequencies, and can happily reproduce the full spectrum at full amplitude all the way down to DC. Second, the TRW does not have any spurious delayed release of energy, so its bass quality is inherently correct and tightly defined, without any phony boom or overhang. And the TRW also thereby allows you to hear much more information immediately after each bass transient (e.g. the woody timbre of a sounding board), so everything from music to special effects sounds much more real. Third, the TRW does not steal any energy from the initial bass transient, so you get the full dynamic impact of each bass transient, again getting you much closer to sonic reality. Fourth, the time domain waveform put out by the TRW is inherently accurate, instead of inherently screwed up, so its waveform correctly adds up with and coheres with each musical (or sound effects) transient put out by your maim loudspeaker, to give you for the first time in your life a correct, coherent transient. This last point might seem to be the most subtle sonically, but it turns out to actually be the most pervasive, affecting more sounds and more of your listening than you would ever have suspected (as we'll explain below).

So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

C. Opposites in Excursion Limits

With conventional subwoofer cone drivers, the cone excursion increases dramatically as the frequency goes lower, for the same power output level. But, as you know, cone drivers have severe limits on the amount of cone excursion they can endure. As cone excursions get larger, various distortions set in, from nonlinearities in the suspensions, and from nonlinearities in the motor (comprising the magnet and voice coil system). Then, as cone excursions get yet larger, cone drivers hit an abrupt stone wall limit, much like amplifier clipping, where they bottom out and simply cannot go any farther (and, if they reach this point, then their distortion gets really gross).

The TRW subwoofer is just the opposite. It inherently does not have any excursion limits. The TRW's effective excursion can effortlessly get larger and larger and larger, as the reproduced frequency goes lower. Indeed, the TRW inherently can put out pure DC, and in so doing its effective excursion reaches infinity, without effort, without distortion, and without any limits.

Since subwoofers do have to endure (thanks to basic laws of physics) dramatically increasing excursions when reproducing progressively lower bass frequencies (see discussion below), it is incumbent upon any driver, hoping to function as a true subwoofer, to be able to correctly handle very large, indeed indefinitely large, excursions. The TRW can do this intrinsically and easily, whereas conventional subwoofer drivers cannot do this at all. Again, it is the TRW that is right, and the oppositely behaving conventional subwoofer drivers that are wrong.

So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

D. Opposites in Low Frequency Reach

In conventional subwoofers, the two factors mentioned above, reactance and excursion limits, each conspire, and both compound together, to set limits on how low in frequency the subwoofer can go. That's why even the biggest, baddest, most expensive subwoofers are doing well if they can make it down to 20 Hz, and simply cannot reach significantly below 20 Hz.

The TRW subwoofer is just the opposite. The TRW reaches all the way down to zero Hz (DC), and does so effortlessly, since it reaches down to DC as part of its intrinsic nature. The TRW is just the opposite in that it does not have any reactance at very low frequencies, and also in that it does not have any excursion limits.

Note that there are literally an infinite number of octaves below 20 Hz, down to DC, and the TRW inherently and easily covers this spectral span of an infinite number of octaves below 20 Hz, whereas conventional subwoofers cannot cover this span at all. A subwoofer is supposed to reach as low in frequency as is sonically important, and we'll see below why this requires frequencies way below 20 Hz, indeed nearly down to DC. So a subwoofer that cannot cover these many, sonically important octaves below 20 Hz is not really a subwoofer at all, whereas the TRW that inherently covers these many octaves easily is just the opposite, and does have this capability that every subwoofer worthy of the name should have.

So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

E. Opposites in Transient Response and Accuracy

As mentioned above, all conventional subwoofers have reactances which make it inherently impossible for them to achieve correct bass transient response, and thereby also make it inherently impossible for them to reproduce bass accurately. Furthermore, these reactances also make their bass energy occur in the wrong phase and at the wrong time. This means that the sonic contribution from all conventional subwoofers inherently cannot possibly add correctly to the sonic signal put out by the main loudspeakers. And this in turn means that the composite sonic signal will necessarily be inaccurate. It also means that the bass energy from conventional subwoofers inherently cannot possibly form the correct pedestal foundation for any and every musical transient and sound effects transient, so these transients (from your system as a whole) cannot possibly achieve the correct dynamic impact, correct peak energy and shape, nor correct sonic quality.

The TRW subwoofer is just the opposite. Rather than it being inherently impossible to achieve correct transient response, the TRW instead is completely the opposite in that it inherently has perfect bass transient response, so it does achieve virtually perfect bass transient response, and does so with ease. This means that the TRW inherently produces virtually perfect bass accuracy. It also means that the sonic contribution from the TRW subwoofer inherently occurs in the correct phase and time, to add correctly to the sonic signal put out by the main loudspeakers. And this in turn means that the bass energy from the TRW inherently does form the correct pedestal foundation for any and every musical transient and sound effects transient, so all these transients (as put out by your system as a whole) can and do easily achieve the correct dynamic impact, correct peak energy and shape, and correct sonic quality.

A crucial factor, in being able to achieve accurate bass transient response, is having frequency response all the way down to DC. A subwoofer like the TRW, which does inherently have frequency response down to DC, can correctly reproduce a step waveform, which is the basic test waveform for evaluating bass transient performance. Any subwoofer like conventional subwoofers, which inherently cannot achieve response down to DC and fail to do so by many octaves (indeed an infinity of octaves), cannot correctly reproduce a step waveform (again, the test waveform for evaluating bass transient response), and therefore cannot correctly reproduce any bass transient from program material.

Furthermore, conventional subwoofers, in the portion of their low frequency response that rolls off and fails to extend down to DC, happen to roll off at a steep rate of 12 dB per octave or worse, and any subwoofer that exceeds a 6dB per octave rolloff steepness will commit even further errors in its bass transient response, which are seen in the step test waveform as overshoot below the zero axis, and possibly also ringing thereafter. The TRW does not have these steep rolloffs, so its transient response does not have overshoot and ringing that make the transient response of conventional subwoofers inaccurate in these further ways.

As we'll discuss later, accurate bass transient response is audibly crucial, for all kinds of music and sound effects. Every kind of music and sound effect is continually changing, so every sound we care about is a transient, not a steady state tone. This means that the transient response of a loudspeaker, including a subwoofer, crucially affects the correctness, accuracy, naturalness, and reality of every sound we hear from our systems.

In all these aspects of transient response, it is the TRW that is right, and conventional subwoofers that are wrong. So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

F. Opposites in Multitasking

Another example of opposite behavior is multitasking. This is probably the most fundamental conceptual distinction between the TRW as opposed to conventional subwoofers. But, because it is a somewhat abstract concept, it might be tricky for you to understand, and tricky for me to adequately convey. So let's start with a simplified rough analogy.

F.1. Two Tasks for One Engine

Imagine that you are blowing out the candles at your birthday party. The engine you use is (simply speaking) your mouth, and you focus all of its effort on just one task, blowing as much air as you can as fast as you can, so you can output enough acoustic energy to blow out the candles pretty easily. But suppose now that you instead assign two distinct tasks to that same engine, your mouth. Suppose that you try to give your thank you speech, to the assembled guests who have just sung you happy birthday, at the same time that you try to blow out the candles. You are still outputting an air stream from your mouth, in that process we call talking. But, in order to make you speech intelligible, you have to accurately modulate and control the air output stream coming from your mouth, creating a specifically and accurately modulated signal that we call talking. Suddenly, because you have assigned one engine (your mouth) to do two distinct tasks, you will become far less effective at outputting enough energy in your pushed out airstream to blow out the candles. Moreover, since it is imperative that your modulated speech signal be understood, the task of accurately modulating your mouth's output airstream (in the process we call talking) becomes the dominant task, taking precedence over how much energy you can output for the other, now secondary, task of blowing out the candles. Thus, your effectiveness at the task of blowing out the candles takes a huge nosedive, merely because you are trying to multitask with your single mouth engine.

Conventional subwoofers also multitask, assigning two distinct tasks to one engine. The one engine, comprising voice coil and cone diaphragm, is assigned the task of moving as much air as it can, in order to generate adequate sound intensity at low frequencies (that's like using your mouth to blow out the candles). But, in conventional subwoofers, this same engine is also assigned the second and very distinct task of modulating the airflow, so that the bass signal is reproduced (that's like talking by using your mouth to modulate the airflow). Moreover, since the bass signal must be accurately reproduced, it is the modulation task that becomes dominant, and takes precedence over the blowing task. This makes the conventional subwoofer cone driver much less effective at its other task, blowing enough airflow energy to adequately create the large energy that bass reproduction requires (like blowing out the candles).

To understand this better, simply visualize a conventional cone subwoofer driver playing a 40 Hz bass sine wave. The cone cannot simply fly back and forth willy-nilly, trying to be as energetic as possible at the one task of blowing as much air as possible, in order to be as effective as possible in creating acoustic bass energy. Instead, because this driver's single engine also has the second task of correctly modulating the airflow to reproduce as signal, the cone is constrained to go back and forth in its excursion at a cycling rate of 40 Hz, no more nor less, in order that it may accurately modulate the airflow at a 40 Hz rate, and thereby reproduce the 40 Hz signal.

Next, visualize that same driver reproducing a 20 Hz sine wave, half the frequency. Because the driver's single engine has been assigned a multitasking role, it must correctly modulate the signal, even while it does the best it can at the second task, generating whatever acoustic energy it can. This means the cone is constrained to go back and forth at half the cycling rate, 20 Hz, thereby taking twice as long to complete its excursion.

F.2. The Excursion Curse

Now, a dynamic driver's motor, like many other motors, operates in a natural acceleration mode. It produces a constant acceleration of the cone diaphragm, for a given input signal level, since (as you'll recall from high school physics) a constant force (which comes from the given input signal level through the voice coil sitting in the magnet's field), applied to a constant mass, produces a constant acceleration.

But this natural acceleration mode means that the multitasking, assigned to conventional subwoofer drivers, creates a curse for conventional subwoofer drivers, a curse that so severely limits the capabilities of conventional subwoofers to function as true subwoofers that they scarcely deserve the name subwoofer. As just discussed above, the multitasking assigned to conventional cone drivers means that they must track the signal (in order to accurately modulate the bass energy flow they are generating). And this in turn means that, when reproducing bass at half the frequency (one octave lower), conventional cone drivers are constrained to take twice as long a period of time to make an excursion.

Why does this create a curse for conventional subwoofer drivers? Because a constant acceleration applied for twice as long a period of time results in the cone traveling at a way higher velocity. Now, higher velocity per se is not that problematic (and indeed is beneficial in one technical sense, helping to maintain flat frequency response to lower frequencies, even in the face of severely declining radiation resistance). But the real kicker is the next, inevitable step imposed by the laws of physics. A way higher velocity, imposed for twice as long a period of time, results in a way, way higher cone excursion distance.

You'll recall from high school physics that excursion distance traveled is proportional to the period of time squared. Thus, as the bass frequency to be reproduced goes lower, here by half, the time for each excursion doubles, and the distance of each excursion thereby quadruples (other technical factors can make woofer excursion increase by even more than four times, or less, but the basic point here stays valid). In other words, this simple lengthening of the time period for each excursion (caused by the assignment of multitasking to the driver, and the driver's consequent obligation to track the signal it is modulating) in turn causes a huge increase in the distance of each excursion, as the bass frequency to be reproduced goes lower.

The simple conceptual fact that, in conventional subwoofers, the driver is assigned multitasking, and is thereby constrained to take twice as long a period of time per excursion when the bass frequency to be reproduced goes down by half, means that its excursion will quadruple (more or less) when this subwoofer driver is asked to merely reproduce bass energy one octave lower.

As discussed above, all cone drivers are really very limited in their maximum achievable excursion. Thus, this quadrupling of excursion, brought on by the assignment of multitasking and consequent doubling of excursion time for each octave, becomes a true curse, the nemesis of conventional subwoofers. It takes a lot of effort for the driver to make this hugely bigger excursion, it stresses the driver, and all this effort and stress soon result in severe limits on how big an excursion the driver can make, as it first distorts and then hits a stone wall (this in turn severely limits how low in frequency the subwoofer can go, and how loud it can play bass).

Thanks to the assigned multitasking, conventional subwoofer drivers run out of excursion capability very quickly when trying to reproduce frequencies that are in true subwoofer territory. So subwoofers using conventional drivers have dubious claim to the pretense of even being true subwoofers at all.

F.3. TRW Single Tasking

The TRW subwoofer is just the opposite. It is not forced to go to higher velocities as the frequency goes lower. It is not forced to go to higher excursions as the frequency goes lower. It so happens that the TRW does automatically increase its effective excursion as the frequency goes lower, but it experiences no stress or difficulty in making these larger and larger effective excursions. And there is no abrupt excursion limit with the TRW, in fact no limit at all (the TRW's effective excursion automatically approaches infinity, as the frequency approaches DC, without any stress or difficulty). Indeed, the TRW actually benefits from these larger excursions at lower frequencies, rather than being cursed by them as conventional subwoofer drivers are.

How can all this be so? How can the TRW be so different, so opposite to conventional subwoofer drivers, in handling the increasing velocity and curse of runaway excursion that worsens at lower frequencies? And how can the TRW, rather than being constrained by the severe and abrupt excursion limits that are the nemesis of conventional subwoofer drivers, instead welcome and actually benefit from increased excursion, all the way to a mind-boggling infinite excursion?

The answers take us back to the fundamental conceptual distinction that started this chapter. Conventional subwoofer drivers multitask, assigning two distinct tasks to one engine, and this is at the conceptual root of the curses that these drivers face with respect to velocity and runaway excursion, which then run smack into the mechanical limitations that severely limit the maximum excursion of these drivers.

But the TRW is fundamentally just the opposite. It does not multitask a single engine. Instead, the TRW has two separate engines, and it assigns a single task to each engine. Thus, each engine in the TRW can perform its single task optimally, without being constrained or compromised by also having to perform a second distinct task. It's like having two people with two mouths, one to optimally perform the single task of blowing out the birthday candles with maximum force, without having to worry about (or compromise for the sake of) the second distinct task of modulating any signal -- and another to optimally perform the single task of modulating a voice signal to give a thank you speech, without having to worry about the second distinct task of blowing out any candles.

How, specifically, does the TRW employ two engines to perform these two distinct tasks? The TRW subwoofer looks for all the world like an ordinary electric fan. Like all electric fans, the TRW uses a motor to rotate the fan with its blades. This motor is thus assigned the single task of blowing air, of supplying all the large amount of energy for the airflow needed to generate acoustic bass (like assigning your mouth to the single task of blowing out birthday candles). Then, the blades of the TRW's fan have variable pitch, just like the propeller blades on airplanes. This variation in blade pitch modulates the bass energy, thus tracking the bass signal. And this variation in blade pitch, this modulation of the bass signal, is accomplished in the TRW by a separate motor, dedicated to this single task (like assigning a second separate person with a distinct mouth to perform the distinct task of giving a thank you speech). This separate motor, that is assigned to modulate the airflow, and thereby track and reproduce the input signal, can do its job optimally, without having to work hard to create the airflow that furnishes the large amount of acoustic energy required for bass.

But the big story here involves the separate TRW motor that drives the fan rotation, which is responsible for generating the airflow and acoustic bass energy. It can continue rotating at full speed, and hence optimally supply bass energy at full effectiveness, regardless of the frequency of the bass signal, and regardless of how the modulation is supposed to occur to reproduce that signal, since it is not constrained by also having to perform this second task of signal modulation.

Thus, the TRW is just the opposite of conventional subwoofers. With the multitasking assigned to conventional subwoofers, we saw that the cycling periodicity of the cone excursion creating the airflow had to change, lengthening (slowing down) as the bass frequency went lower, since the cone also had to perform the distinct task of tracking and modulating the bass signal as it changed frequency. But here, in the TRW, the fan's rotating velocity creating the airflow does not have to slow down its rotational drive at all, as the bass frequency to be reproduced goes lower, so the fan motor and fan can continue rotating at maximum effectiveness for optimally creating acoustic bass energy.

F.4. TRW Improvements as Frequency Goes Lower

We also saw that, with conventional subwoofer drivers, their cone velocity went way up, and their cone excursion went way, way up, as the bass frequency to be reproduced went lower, until very soon the driver excursion limits were reached. This severely curtailed the ability of conventional subwoofer drivers to play low bass and to create the large acoustic energy required by low bass, and since these are the two primary responsibilities for subwoofers, this means that conventional subwoofers cannot even perform their primary responsibilities, so are scarcely worthy of being called real subwoofers in the first place.

Again, the TRW is just the opposite. Its rotating fan velocity, which drives the airflow, does not go up as the bass frequency to be reproduced goes down. Furthermore, the TRW is also just the opposite in that it does not run into severe excursion limits as the bass frequency goes lower.

Indeed, the TRW's effective excursion can, in one sense (excursion per cycle of bass signal), continue to increase indefinitely as the bass frequency goes lower, without any of the effort or strain or limits that conventional subwoofer drivers are cursed by. The TRW's effective excursion per cycle can even effortlessly approach infinity (!!), as the bass frequency being reproduced approaches DC. How can the TRW do this? Because the TRW does not multitask, and assigns a separate engine to each task, the fan's rotational velocity can remain constant and unchanged, even as the bass frequency goes lower. Since the TRW fan's rotational velocity per second (per unit time) stays constant, its rotational bite of airflow per signal cycle increases automatically, as the time per signal cycle increases (gets longer), when the bass frequency goes lower. As the bass frequency to be reproduced gets lower and lower, approaching DC, the TRW fan's bite of airflow per signal cycle automatically gets larger and larger, without effort and without limit, finally approaching infinity as the bass frequency approaches DC.

Thus, the TRW, with its separate motor creating the airflow and bass energy, actually benefits from the bass frequency going lower. This is the complete opposite from conventional subwoofer drivers, which are severely penalized in performance as the bass frequency goes lower.

We can look at the contrast as follows. With conventional subwoofer drivers, the motor creating the airflow and bass energy is constrained to slow down its cycling as the bass frequency goes lower, since this motor also has been assigned the second distinct task of tracking and modulating the bass signal, and therefore there is only ***one*** excursion cycle per bass signal cycle. With the TRW, the motor creating the airflow and bass energy is not so constrained, since it is not assigned the second distinct task of tracking and modulating the bass signal, so it can make ***many*** excursion cycles (fan rotations) per bass signal cycle. Furthermore, since the TRW fan's rotational speed can stay constant per unit time as the bass frequency goes lower, the TRW fan not only can make many excursion cycles per bass signal cycle, but also its number of excursion cycles, per bass signal cycle, automatically keeps ***increasing*** as the bass frequency to be reproduced goes lower, thereby automatically increasing the TRW subwoofer's volume of air moved, as the bass frequency goes lower.

As you know, bass frequencies require a lot of energy, and require a lot of air to be moved. In one corner we have the conventional subwoofer driver, whose physics make its excursion increase hugely as the bass frequency goes lower, but which soon hits a stone wall at say 1 inch excursion. In the other corner we have the TRW subwoofer, whose physics are not adversely affected (indeed are benefited) by the bass frequency going lower, and which then also has infinite effective excursion capability. So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

G. Opposites in Factors Limiting Bass Quantity

Conventional subwoofers face a number of factors, which conspire to severely limit the quantity of bass they can produce (i.e. how loudly they can play), especially at exactly those low frequencies where subwoofers are supposed to be able to do their job.

First, their steeply declining radiation resistance means that they become much less effective at coupling to the air at progressively lower frequencies, and you can't create loud acoustic levels in the air when you can't couple to the air in the first place.

Second, their driver's puny and severely limited excursion capability, exacerbated by the fact (discussed above) that their driver's excursion intrinsically gets way, way larger as the bass frequency goes lower (even for the same modest loudness level), means that they cannot play loudly at low frequencies -- and means that their ability to create bass quantity gets severely reduced, merely by the frequency going lower, so that they intrinsically cannot play bass that is both low in frequency and loud. Since bass frequencies inherently require large amounts of energy to reproduce properly, a proper subwoofer needs to be able to play low frequencies loudly. Furthermore, as the Fletcher-Munson curves show, human hearing becomes much less sensitive at low bass frequencies, so a proper subwoofer also needs to play low frequencies loudly in order to even be heard.

Third, conventional subwoofer drivers also have other inherent physical factors that can prematurely limit their bass loudness capability. For example, there are thermal constraints on a woofer driver being able to play loudly for a reasonable length of time. Most cone drivers are sadly inefficient, which means that most of the dissipated power put into the driver (by your power amplifier) becomes heat within the driver, instead of becoming acoustic loudness radiated by the driver. If voice coils get too hot, they can destroy the driver, melting the glues or plastic parts, setting combustible parts up in smoke, etc.

Fourth, the fact that all conventional subwoofer drivers are assigned a multitasking role for their single engine (as discussed above) thereby forces your power amplifier, which drives this single engine, to also be assigned the same multitasking role. Your power amplifier has to perform two distinct tasks when driving these conventional subwoofer drivers. Your power amplifier must modulate the motion of the driver, to track and reproduce the bass signal. And, on top of that, your power amplifier must also furnish all the energy needed by the driver to perform its second task, creating the airflow and large acoustic energy required for bass. This latter task is of course what creates the loudness or quantity of bass.

Most power amplifiers have trouble furnishing enough energy to perform this latter task adequately, so the power amplifier often becomes yet another factor limiting bass quantity. Note that amplifiers with very high power (and high current) ratings are often credited with providing better bass from a given conventional loudspeaker, so this proves that lesser amplifiers fall short of being able to supply the huge amount of energy (usually in the form of current) required for this latter task, and become yet another factor limiting the bass quantity available from conventional subwoofers. This limitation also of course applies to any power amplifiers built into the subwoofer, which might not be up to the challenge of the subwoofer they are mated with.

Fifth, since conventional subwoofers are very inefficient, only a small percentage of the power supplied by your power amplifier (or the built-in power amplifier) gets converted into bass acoustic energy. This in turn forces your power amplifier to work very hard, having to put out many watts of bass energy for every acoustic watt of bass loudness actually put out by the subwoofer. Thus, the limits for subwoofer bass loudness, due to your power amplifier reaching its power and/or current limits, are reached much sooner, at a much reduced loudness level, thanks to the inefficiency of conventional subwoofers.

Furthermore, a subwoofer's inefficiency gets worse as its cabinet enclosure gets smaller, as its cone area gets smaller, and as its bass frequency extension goes lower (Hoffman's iron law). Nowadays the trend is to make most subwoofers with small drivers (smaller than 18 inches), and with small enclosures (to ensure domestic visual acceptability), and with an advertised reach down to 20 Hz (to make it saleable as a so-called subwoofer). So, nowadays, all of these three parameters conspire to make subwoofers extremely inefficient, which thereby makes them extremely demanding upon your power amplifier (or the subwoofer's built-in amplifier), and thereby in turn limits more severely the maximum bass loudness this subwoofer can in practice achieve.

The TRW is just the opposite, in all these factors that limit the quantity of bass that conventional subwoofers can create.

First, rather than its radiation resistance declining very steeply at lower frequencies, as with conventional subwoofers, the TRW's radiation resistance instead does not decline steeply at lower frequencies. Indeed, the TRW's effective area actually increases at lower frequencies, as opposed to conventional subwoofer drivers, whose area of course remains constant at lower frequencies. Thus, the

TRW couples much better to the air than do conventional subwoofer drivers. So the TRW can create much larger quantities of bass (i.e. much louder bass) than conventional subwoofers can.

Second, rather than having a puny and severely limited excursion capability, as with conventional subwoofers, the TRW instead does not have a puny and severely limited excursion capability. Indeed, the TRW does not have any excursion limit at all, and can easily (without effort, strain, or distortion) approach infinite excursion as the frequency being reproduced goes lower and approaches DC. Thus, the TRW can play bass much, much louder than conventional subwoofers can. And the TRW's ability to play bass loudly does not decline as the bass frequency goes lower, as it intrinsically does with conventional subwoofers. So, contrary to conventional subwoofers, the TRW can play bass that is both low in frequency and loud, and can do so easily and effortlessly, without strain or distortion.

Third, the TRW does not have the same physical factors limiting bass loudness as conventional subwoofer drivers do. Because the TRW does not assign multitasking to one engine as conventional subwoofers do, but instead has two engines, each devoted to a single task, the TRW does not have the same physical limitations.

In particular, the voice coil responsible for modulating the signal in the TRW is ***not*** also responsible for performing a second task (as it is in conventional subwoofers), the task of creating the airflow that supplies the energy for bass loudness. In the TRW, a second independent engine (the rotating fan motor) is responsible for this second task, which supplies the energy for bass loudness. This second engine does not at all face the same limiting factors that a voice coil, spider suspension, etc. face. Instead, this second engine in the TRW, responsible for creating the bass loudness, can create much higher energy airflow, hence much louder bass, before reaching its limiting factors, which are wholly different in nature and which cut in at a much higher airflow level, hence a much higher bass loudness level (think of the effectiveness of electric motor fans at creating large airflows, e.g. for wind tunnels).

Thus, the TRW can play bass much, much louder than conventional subwoofers, because it does not face the same limiting physical factors, thanks in large part to the fundamental conceptual contrast vs. conventional subwoofers (discussed above), wherein the TRW has two engines instead of one, each engine optimally dedicated to just one task -- and the engine dedicated to generating bass loudness does not have to also contain parts for modulating the signal, parts (e.g. a voice coil and spider) which have severe loudness limitations. The TRW does have some physical limitations involving other factors, but they do not limit loudness until the TRW achieves much, much louder levels of bass than conventional subwoofers can even dream of approaching.

Fourth, the fact that the TRW, in fundamental conceptual contrast to conventional subwoofers, does not multitask, means that the power amplifier in turn, which drives the signal modulating engine of the TRW, only has to perform signal modulation as its single task. The power amplifier of the TRW does ***not*** have to also supply the energy to create the airflow to create bass loudness, as it does have to do with conventional subwoofers. Thus, the TRW is not limited in its bass loudness capability by any power amplifier limitations at all. Also, the issues of conventional subwoofer inefficiency putting a further strain and a further limit on the power amplifier's capabilities, hence a further limit on bass loudness, become non-issues for the TRW. And the issues of power amplifier inefficiency, which also limit a power amplifier's drive capabilities to produce loudness from conventional subwoofers, become non-issues for the TRW, since the power amplifier is not at all involved in the task of producing bass loudness.

In the TRW, bass loudness chiefly comes from the task performed by a distinct engine, an engine which is not powered by any power amplifier. Instead, this distinct engine, the rotating fan's drive motor, gets its energy directly from the powerline. So virtually all the energy available from the powerline is directly at the disposal of the TRW's fan motor, to create bass loudness. And the powerline is a far greater source of energy than any power amplifier, however huge, could hope to be. Note that any power amplifier has to get all its input energy from the same powerline, and every power amplifier has less than 100% efficiency (often far less), so some of the energy available from the powerline cannot make it to the output of the power amplifier (but instead produces heat inside the power amplifier, which in turn limits the maximum energy that any power amplifier of reasonable size and cost can put out).

The maufacturer has measured the TRW-17 subwoofer as putting out a loudness level of 115 dB, at 1 Hz (!!!), with low distortion. No other subwoofer comes even close to this low bass performance.

Fifth, the efficiency of the TRW is also far greater than the efficiency of conventional subwoofers. Thus, for a given powerline capability and a given power amplifier size and cost, the TRW can produce far higher bass loudness than a conventional subwoofer can.

The TRW does employ a power amplifier, but only for the single task of signal modulation. Naturally, there are some limits to this power amplifier, and some inefficiencies with the signal modulation process that this power amplifier must drive. But these issues primarily affect only the signal modulation process, and do not directly affect the loudness (bass quantity) capability, since the latter comes primarily from a different engine, the fan motor powered directly by the powerline. The manufacturer recommends that a 200 watt power amplifier is sufficient for driving (controlling) the signal modulation task, even for the huge loudness levels that the TRW is capable of (in contrast to conventional subwoofers, which require 1000 watt power amplifiers to achieve far less loudness).

As you can see, the many factors, which severely limit the loudness and bass quantity capability in conventional subwoofers, simply do not apply to the TRW. The TRW and conventional subwoofers are opposites in being limited by these factors. With respect to these factors, it is conventional subwoofers which are limited hence wrong for obtaining a reasonable quantity of bass (especially at the low bass frequencies which it is a subwoofer's very job to handle well), and it is the TRW which is right, by not be thusly limited in bass quantity by these factors. It is the primary responsibility of subwoofers to play low bass and to create the large acoustic energy required by low bass, so this means that conventional subwoofers cannot even perform their primary responsibilities, and therefore are scarcely worthy of being called real subwoofers in the first place. So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

H. Opposites in Pressure and Volume, hence Bass Quality

As a final example of inherently opposite performance, consider pressure and volume. Conventional subwoofers are high pressure pumps, with a high excursion, small diameter piston madly flailing away as it pumps a small air volume with high pressure. This is exactly the opposite of how most natural bass sounds are actually produced, and is the opposite of how naturally produced bass quality actually sounds to us. The bass from a bass viol (plucked or bowed), from a grand piano's large sounding board, from an organ pipe, from a bass drum, are all produced live by large radiating surfaces or volumes, operating at low pressure. Even a cannon shot or similar sound effect, though perhaps produced by a high pressure event at its source, becomes a relatively low pressure, large wavefront by the time it reaches you in open air (assuming you are located at sufficient distance to hear it without having your hearing damaged).

Incidentally, a bass horn, acting a transformer to convert high pressure from the driver into low pressure at the horn mouth, can reproduce the correct low pressure bass sound of the original live event, but practical bass horns cannot extend below 40 Hz, so they make wonderful woofers but are useless as subwoofers.

Conventional subwoofers, with their small area pistons pushing a high pressure, small volume of air at you in the confines of a small room, simply cannot replicate or correctly reproduce the low pressure sound of the original bass event. Thus, conventional subwoofers intrinsically cannot recreate the correct bass quality, nor high quality bass.

The TRW subwoofer is just the opposite. It intrinsically operates in a low pressure, high volume mode, exactly like the original live bass sounds, and the opposite of conventional subwoofers. Sonically, it is instantly obvious that the bass quality from this low pressure TRW subwoofer sounds natural and has the correct bass quality, from all bass events, be they a bass viol, the large radiating sounding board of a grand piano, the huge volume moved by a bass organ pipe, a bass drum, or even a cannon shot from a film soundtrack. And, in direct comparison, it is instantly obvious that the bass quality from conventional subwoofers sounds all wrong in quality, like a high pressure, low volume pump flailing away in a vain attempt to produce some semblance of bass sound.

Again, the low pressure, high volume TRW is just the opposite of conventional high pressure, low volume subwoofers, and it is the TRW that is right and the conventional subwoofers that are wrong. So, which is the real subwoofer, and which is the pretender? As we said, the TRW is the only subwoofer.

Part II: How the TRW Works

The design concept of the TRW is radically new for a subwoofer, and radically different from conventional subwoofers, indeed so different that doubting Thomases can't see how the TRW could possibly work as an audio subwoofer.

But the basic technologies employed by the TRW are actually old, well established, and well proven.

A. Proven Technologies

The engine that provides the airflow, hence the bass energy, in the TRW is simply a fan, directly powered by an electric motor, which in turn is directly powered by the powerline. Electric fan technology is very old, in fact several decades older than the moving coil loudspeaker driver employed by conventional subwoofers. And the electric fan has been very well established and well proven, for over a century, as a very effective and efficient mover of large quantities of airflow. The electric fan is used almost universally, for small applications like venting your computer case, for medium applications like ventilating or exhausting your domestic room or attic, and for large applications like power station cooling and wind tunnels. If any doubting Thomas thinks that fan technology cannot move enough air to create thunderous bass in a domestic room, let him try to stand upright in a wind tunnel.

The second engine in the TRW, which tracks the audio signal and modulates the airflow in accurate sympathy, is simply variable pitch for the fan blades. This variable pitch blade technology has been employed and proven for nearly a century, for example in airplanes, where the propeller blade pitch is varied to suit varying conditions. Airplane propeller blades even reverse their pitch, thereby providing negative airflow, to very effectively brake the airplane after landing touchdown (even more effectively than the old fashioned technology of wheel brakes can do). If any doubting Thomas thinks that variable pitch blades cannot effectively modulate airflow, to reproduce a positive and negative audio signal waveform, let him try to stop a heavy airplane, after landing touchdown, with old-fashioned wheel brakes alone.

Doubting Thomases will be further reassured by the fact that these two old technologies have already been successfully combined in a loudspeaker (though not a subwoofer), over half a century ago, a loudspeaker that can play extremely loud and put out huge amounts of acoustic energy. The moving vane loudspeaker, used extensively in World War II, used one engine to move air, and a second engine to modulate the airflow via a variable pitch blade, just as the TRW subwoofer does. And this moving vane loudspeaker, using the same basic technologies united together as in the TRW subwoofer, could generate such huge acoustic energy and loudness that it was used to communicate between warships that were located far (perhaps miles) apart! If these same technologies as used in the TRW have long ago been proven to be able to generate this kind of acoustic energy and loudness over the open air space above the ocean, then doubting Thomases can be reassured that the TRW can generate all the acoustic bass energy you could possibly want within the confines of a domestic room space.

The TRW drives its rotating fan directly by an electric motor, working straight off the powerline, at constant rotational velocity. The TRW modulates the fan blade pitch with a voice coil, which is mechanically linked to the variable pitch blades, and which is driven by a conventional power amplifier responding to the bass audio signal input.

As the blade pitch is modulated in response to the bass signal, the blades push more or less air forward, or more or less air backward (for the negative portions of an AC bass signal waveform). Note that the TRW fan can happily and effortlessly thereby reproduce bass signals of arbitrarily low frequency (as discussed above, this is the complete opposite of conventional subwoofers, which get into progressively worse trouble, in many ways, as the bass frequency to be reproduced goes lower). The TRW can even happily, effortlessly, and accurately reproduce DC (zero Hz), by simply holding the blade pitch fixed while the fan continues to rotate.

B. Comparisons with Conventional Subwoofers in Air Volume

The diameter of the fan in the TRW is about 19 inches. So it's instructive to compare its performance, in moving air and thereby creating acoustic bass energy, with a conventional subwoofer driver of 18 inches diameter. An 18 inch diameter cone driver also happens to be the maximum size employed by conventional subwoofers, even huge (and hugely expensive) monsters, so this comparison pits the TRW performance against the very best that conventional subwoofer technology can offer.

In the following comparison, we will deliberately oversimplify. The idea is to convey, as clearly as possible, the key operative principles at work here. This means omitting details which would add more confusion than information.

B.1. Batch of Air, per Excursion vs. per Revolution

Assume that the 18 inch cone woofer makes a 1 inch excursion, and that the TRW's fan blades are likewise set at a 1 inch pitch. Assume that the circular area of the cone piston of the 18 inch driver (discounting its surround area) is equivalent to the circular area within the 19 inch diameter of the TRW's fan (discounting its hub area).

Consider first the cone of the 18 inch woofer. With one excursion, it grabs a batch of air, and pushes it forward. How much air does it grab in this batch? The volume of air it moves is basically the area of the cone times the 1 inch excursion. Consider next one of the fan blades of the TRW's fan. With one revolution of the fan, this blade cuts into and grabs a batch of air, and pushes it forward. How much air does it grab in this batch? The volume of air it moves is basically the area swept by the fan blade in one revolution times the 1 inch bite from the blade pitch. As you can see, the cone of the large 18 inch woofer is closely equivalent to one fan blade of the TRW's 19 inch fan, both moving basically the same volume of air.

Note that this equivalent volume of air is moved by the cone woofer in each of its ***excursions***, and is moved by one of the TRW's fan blades in each of its ***revolutions***. But that's comparing apples to oranges (excursions to revolutions). So, before we can make the comparison complete, we first have to find a way to convert between excursions of the woofer (e.g. the number of excursions per second the woofer makes) and revolutions of the TRW fan (e.g. the number of revolutions per second it makes). After doing this conversion, then we can compare apples to apples, for example the volume of air moved by the cone woofer per ***second*** vs. by the TRW fan per ***second***.

B.2. Air Volume per Second

To make this conversion, we first have to pick some bass frequency being reproduced. So let's start with 60 Hz, which is certainly at the high end of the spectral range any subwoofer might be expected to cover. At 60 Hz, the cone woofer makes 60 cyclic excursions per second, so its total volume of air pushed per second is 60 times the amount of air it pushes in each excursion. The TRW fan makes about 12 revolutions per second, and it has 5 blades (not just the one blade we considered above). So its total volume of air pushed per second is 12 times 5 = 60 times the amount of air that one of its blades pushes in each revolution.

Thus, at 60 Hz, the two types of woofers are equivalent again, only this time we are comparing apples to apples, and they are equivalent in terms of air volume pushed ***per second*** (as well as still being equivalent in terms of the above apples to oranges comparison, the volume of air pushed by the cone woofer per excursion vs. by one of the TRW fan blades per revolution).

B.2.a. Lower Bass Frequencies

Then, let's see what happens when we cut the bass frequency in half, to 30 Hz. The TRW fan continues to rotate at a constant velocity, so its total bite of air volume per second remains constant, and is the same at 30 Hz as it was at 60 Hz. The radiation resistance of the TRW fan falls linearly with frequency, so its coupling to the room air is half as good at 30 Hz as it was at 60 Hz. Thus, the effective total bass output of the TRW is half as much as it was at 60 Hz (later we'll discuss how the phenomenon of room gain kicks in to make the TRW pretty flat to very low frequencies).

The cone subwoofer driver, however, in contrast to the TRW fan, does not keep taking a constant number of bites per second as the bass frequency goes lower. Thanks to the fundamental conceptual fact that the cone driver has to multitask (as discussed above), the cone woofer has to track the frequency of the bass signal, so it only makes half as many cyclic excursions per second at 30 Hz as it did at 60 Hz. So this factor already cuts the cone subwoofer driver's output per second in half at 30 Hz, compared to its output at 60 Hz, and compared to the TRW's output at 30 Hz. Then, to make matters worse for the cone subwoofer driver, its radiation resistance falls as the square of frequency (rather than linearly with frequency, as the TRW fan does). Thus the coupling of the cone subwoofer driver to the room air falls by a factor of 4, when the bass frequency goes down by half. So now the bass output of the cone subwoofer driver has fallen by a factor of 8 (2 times 4) at half the frequency.

Now, the cone subwoofer driver can make up some of this lost ground, if it can increase its excursion dramatically. In cone drivers, as discussed above, the excursion does tend to increase as the bass frequency goes lower. The cone excursion tends to increase by about 4 times (oversimplifying here), for each halving of frequency. Thus, ***if*** the cone subwoofer driver were capable of making this much larger (4 times) excursion, it would recapture 4 out of the 8 times poorer output we just saw it suffer. This would mean that the cone subwoofer driver would net out at 2 times poorer output (half the output) at half the frequency, 30 Hz instead of 60 Hz, and that would again make the cone subwoofer driver equivalent to the TRW subwoofer. But can the cone subwoofer driver make this 4 times larger excursion? If its cone excursion was 1 inch at 60 Hz, then it would have to be able to make a 4 inch excursion at 30 Hz, just to stay equivalent to the TRW subwoofer. Very few cone drivers (if any) can make a 4 inch excursion.

Of course, we could cut the bass volume level, so that the cone subwoofer driver was making say only a 1/4 inch excursion at 60 Hz, and thus would be making merely a 1 inch excursion at 30 Hz, which it could surely manage. But then the cone subwoofer driver would still have to make a 4 inch excursion at 15 Hz, just to keep up with the TRW subwoofer at 15 Hz. You see the problem. At some low bass frequency the conventional subwoofer cone driver is simply going to abruptly run out of excursion capability, regardless of how far we reduce the bass volume. And at this low bass frequency, the TRW will charge ahead of the conventional cone subwoofer, for this bass frequency ***and for all lower bass frequencies***.

The TRW subwoofer, in complete contrast and opposition to the conventional cone subwoofer driver, can happily go lower and lower and lower in bass frequency (and at very high bass volume levels), without strain or effort, and without being constrained or curtailed by any excursion limits. Indeed, the TRW subwoofer can effortlessly play all the way down to (and including) zero Hz, i.e. DC.

Furthermore, since the TRW can happily and effortlessly play lower and lower and lower in frequency, there is no need to reduce its bass volume level to keep it within its excursion limits. Thus, we could easily play the TRW loudly by having its blade pitch set at a full 1 inch at 60 Hz, and keeping it there for all lower frequencies.

Therefore, to be fair in comparing the two subwoofer technologies, we should re-state the above conditions of the starting point at 60 Hz. The TRW still has its blade pitch set at a full 1 inch, but we had to re-set the excursion of the cone subwoofer driver at 60 Hz to just 1/4 inch, so that it could still play 30 Hz within its 1 inch excursion capability. Thanks to the cone subwoofer driver's excursion curse, the penalty that it has to pay, for being able to extend its response, just down to 30 Hz from 60 Hz, is to cut its maximum loudness to 1/4 (for all frequencies) of what it had been, when it was equivalent to the TRW at 60 Hz. Thus, already at 60 Hz, the TRW in this re-set example can move 4 times more volume of air than the conventional cone subwoofer driver can, and the TRW would retain this 4 times advantage all the way down to 30 Hz. Then, somewhere below 30 Hz, when the conventional subwoofer driver finally, inevitably does run out of excursion capability, the TRW will charge even farther ahead of the conventional subwoofer, for this frequency and for all lower bass frequencies.

B.2.b. Alternative Starting Frequency

Incidentally, we could alternatively have started the above comparison at a frequency other than 60 Hz. We chose 60 Hz because, at this frequency, the two subwoofer technologies are approximately equivalent, so this makes a conceptually useful starting point, with the two subwoofer technologies diverging somewhere below this frequency, as conventional subwoofer drivers start running afoul of their inherent limitations. For example, if we had used 30 Hz as a starting point for our comparison, then the TRW's performance would have been twice as good as the conventional subwoofer driver, right out of the starting gate, instead of being equivalent as it is at 60 Hz.

Why is this? Because of the fundamental conceptual contrast between the two subwoofer technologies, wherein the conventional subwoofer driver has to multitask but the TRW does not, the conventional subwoofer driver has to track the bass signal it is modulating, so its excursion cycling has to slow down at lower frequencies. This means that, at 30 Hz, the conventional subwoofer driver can only make 30 excursion cycles per second. Meanwhile, since the TRW does not multitask, its fan (that is responsible for creating the volume airflow) does not slow down for lower frequencies, so at 30 Hz the TRW is still making 60 blade-revolutions per second (12 fan revolutions per second times 5 blades). Just as we did above, we are assuming here, for our starting point, that the cone subwoofer driver is making a 1 inch excursion, and that the TRW has its blade pitch set to the same 1 inch, and that the driven area of the 18 inch cone woofer per excursion is equivalent to the driven area of one of the TRW's fan blades per revolution as it sweeps its 19 inch diameter circle. Thus, the volume of air driven by the cone driver in one excursion is equivalent to the volume of air driven by one TRW fan blade in one revolution, just as it was above when we used 60 Hz as the starting point for our comparison. And of course the TRW fan still has the same 5 blades as it did above.

Thus, the fact that the TRW fan has a 2 times superiority over the conventional subwoofer driver, when we use 30 Hz as the starting frequency for our comparison, is due entirely to one key factor, namely the fact that the TRW fan does not slow down its revolutions per second when playing lower bass frequencies, here 30 Hz instead of 60 Hz, whereas in contrast the conventional subwoofer driver does have to slow down its excursion cycling per second when playing lower bass frequencies, here 30 Hz instead of 60 Hz. And this key factor, this contrast, is in turn due to the fundamental conceptual contrast between the TRW subwoofer technology and conventional subwoofer technology, namely that the conventional subwoofer driver has to multitask whereas the TRW subwoofer does not.

The conventional subwoofer driver has to also perform the second task of modulating the bass signal, so it has to slow down its excursion cycling in order to track and accurately modulate the bass signal that is now cycling more slowly (at 30 Hz instead of 60 Hz), and thus cannot optimally perform the task of blowing maximum air volume (it has to perform the second task of articulating a thank you speech, while attempting to blow out the candles, so it becomes less effective at blowing out the candles). In contrast and opposition, the TRW fan rotation has only the single task of blowing maximum air volume, so this fan rotation can continue at full speed, even while the bass signal cycling gets slower at lower bass frequencies. The TRW fan rotation can continue to be maximally effective, even at lower bass frequencies, since it does not have to worry about performing the distinct task of modulating the bass signal (this modulation is performed by a separate engine in the TRW, the motor that modulates blade pitch). The TRW fan rotation can concentrate on optimally performing its single task of blowing out the candles, without having to worry about slowing down to perform the distinct task of articulating a thank you speech.

As you can readily appreciate, this last example, wherein the TRW is 2 times more effective when we use 30 Hz as the starting point for our comparison, naturally extends to yet lower frequencies as well. For example, if we were to use 15 Hz as the starting point for our comparison, the TRW's air volume would be 4 times larger than the conventional subwoofer cone driver (this assumes, on behalf of the conventional subwoofer, the unlikely scenario that its bass resonance frequency is below 15 Hz, so that it has flat frequency response to below 15 Hz).

B.2.c. Further Limitations of Conventional Subwoofers

This last example, at 15 Hz, raises a further point. The above discussion does not even take into account a yet further limitation conventional subwoofers suffer in moving air at low frequencies, namely the frequency barrier due to their inherently reactive nature. Their bass frequency response hits a brick wall at their resonance frequency (usually 20 Hz or higher), and plummets below that frequency. In contrast, the TRW does not have any reactive nature at very low frequencies, so its frequency response stays substantially flat to indefinitely low frequencies, indeed down to and including DC. In other words, at (and below) whatever frequency a conventional subwoofer hits its reactive resonance, the TRW's bass quantity performance charges ahead of the conventional subwoofer in two distinct and huge ways. First, the conventional subwoofer has (or soon will) run out of excursion capability, so its volume for all bass, including very low frequencies, must be reduced. Second, the conventional subwoofer's bass output rolls off severely below its resonant frequency, which even further reduces its bass output for very low bass frequencies. Meanwhile, the TRW faces neither of these limitations. The TRW never faces any excursion limitation, so it can play arbitrarily low bass frequencies, and play them very loudly. And the TRW never faces any frequency response rolloff at very low frequencies, so it continues to put out strong, substantially flat bass response, to arbitrarily low bass frequencies.

Incidentally, in conventional subwoofer designs that use vented enclosures, the cone driver excursion beneficially decreases at the frequency of vent resonance, when the vent beneficially loads the driver. But this benefit disappears at bass frequencies below the vent resonance frequency, where the vent unloads, and the cone driver's excursion increases dramatically. Program material actually contains frequencies well below the vent resonance frequency (as we'll discuss below), especially film soundtracks, which contain this very low frequency energy at very strong, loud levels, so excessive excursion and severe excursion limits are still a problem, even for vented conventional subwoofer systems.

B.3. Air Volume per Cycle

We have just discussed the performance comparison, between the two subwoofer technologies, in terms of air volume moved per second. It is also instructive to look at the TRW's performance in terms of air volume moved per cycle of the bass signal. As the bass frequency being reproduced goes lower, the time period of each cycle gets longer, with half the frequency (e.g. 15 Hz instead of 30 Hz) taking twice as long a time period. Since the TRW's fan rotation keeps going at the same speed, regardless of bass signal frequency, this means that the TRW's fan makes twice as many revolutions per signal cycle, when the bass signal goes to half the frequency, four times as many revolutions when the bass signal goes to one-fourth the frequency, and so on, without limit. Thus, the TRW automatically and effortlessly takes more and more revolution bites of air per signal cycle, as the bass frequency goes lower. In contrast, a conventional subwoofer driver can make only one excursion per signal cycle, even as the bass frequency goes lower, and so can take only one excursion bite of air per signal cycle, even as the bass frequency goes lower. As we saw above, the TRW fan takes one blade-revolution bite of air per signal cycle at 60 Hz, two bites per signal cycle at 30 Hz, four bites per signal cycle at 15 Hz, eight bites per signal cycle at 7.5 Hz, etc.

As you can see, the TRW subwoofer moves twice as much air volume per signal cycle for every halving of frequency. And the volume of air moved per signal cycle, by the TRW, automatically and effortlessly keeps increasing, without limit, as the bass frequency being reproduced goes lower. Indeed, as the bass frequency reproduced by the TRW approaches zero Hz (DC), the TRW fan's number of bites per signal cycle, and hence volume of air moved per signal cycle, automatically and effortlessly approaches infinity. This also means that the TRW's effective excursion (per signal cycle, which is also how we look at the excursion of conventional subwoofer drivers) automatically and effortlessly increases, without limit, as the bass frequency goes lower, and also approaches infinity as the bass frequency approaches DC. These dramatic increases per signal cycle are automatic and effortless for the TRW because they are a simple result of the fact that the TRW fan, creating the airflow and bass energy, just keeps rotating at the same speed, regardless of frequency (thanks to the fact that the fan's rotation is not also assigned the distinct task of signal modulation).

In contrast to the TRW's fan rotation, a conventional subwoofer driver cannot keep cycling its excursions at the same speed, as the bass frequency being reproduced goes lower. Instead, it must slow down its excursion cycling as the frequency goes lower, to track the slowing down of the bass signal cycling (thanks to the fact that the single cone driver engine must multitask, and must modulate the signal as well as creating airflow and bass energy). Thus, the only way that a conventional subwoofer driver can increase its volume of air per signal cycle, to compete with the TRW's intrinsic and automatic ability to do this, is to increase its cone velocity and thereby hugely increase its excursion distance, within each excursion cycle and signal cycle. But, as we discussed above, this huge increase in excursion distance increase is very stressful on cone drivers, and very soon drives them to their modest excursion limits, as the bass frequency goes lower.

Because the TRW does not have any excursion limits, it automatically and effortlessly keeps increasing its effective excursion per signal cycle as the bass frequency goes lower, so its bass performance capability does not have any limitations whatsoever as a function of the bass frequency going lower. In contrast, the conventional subwoofer driver has very modest excursion limits, so in attempting to stay competitive with the TRW as the bass frequency goes lower, it very quickly runs afoul of its modest excursion limits per signal cycle, and thereby hits the absolute ceiling of its bass performance capability.

C. Comparisons with Conventional Subwoofers in Coupling to Air

There's another interesting benefit that the TRW realizes, from the fact that the number of air bites it takes per signal cycle keeps increasing, as the bass signal frequency goes lower. As the TRW fan takes progressively more bites of air per signal cycle, the effective radiating area of the fan keeps growing. Thus, the effective area of the TRW's fan "diaphragm" keeps growing, without limit, as the bass frequency goes down. In contrast, the radiating area of a conventional subwoofer driver's diaphragm of course stays constant as the bass frequency goes lower.

This progressive growth, in the TRW's effective radiating area, at progressively lower bass frequencies, is of enormous benefit in the TRW's ability to couple to the air, and to thereby generate real acoustic bass energy in your room, especially at low bass frequencies. You see, as the bass frequency goes lower, the acoustic wavelength in the air gets longer, so a driver diaphragm of a given fixed diameter couples to the air in a weaker and weaker fashion. At low bass frequencies where subwoofers operate, the acoustic wavelengths become so long that an ordinary cone driver, even of 18 inch diameter, couples very weakly to the air, and thus cannot be effective at actually driving the air and creating acoustic bass energy, regardless of how much the tiny cone might flail about.

As a simple analogy, imagine flicking a cherry pit into the air. However fast you flick it, and however far it might travel in its excursion, that cherry pit is not going to push or move much air, because it is physically so small that it does not couple effectively to the air (the air simply gets out of the way of this small moving object, whereas the air could not get out of the way if the moving cherry pit were instead a moving barn door with a large area).

In fact, the laws of physics dictate that, for a diaphragm of fixed diameter and radius and area (as a conventional subwoofer driver is), the coupling effectiveness, measured by a parameter called radiation resistance, falls as the square of the frequency, so it falls (gets weaker) very steeply, as the bass frequency goes lower and the acoustic wavelength gets longer. In contrast, the TRW fan increases its effective radiation area linearly, as the frequency goes lower, thanks to the fact that it takes multiple bites of air per signal cycle (this radiation area increase has been confirmed by the manufacturer's impedance measurements, which show the air load upon the fan at various frequencies). This linear increase in the TRW fan radiating area offsets half of the natural square law decrease dictated by the laws of physics. This means that the TRW subwoofer retains its radiation resistance, its coupling effectiveness to the air, far better than the fixed radiating area cone of a conventional subwoofer driver. With the TRW, the radiation resistance (and coupling effectiveness) falls merely at a gentle linear rate, rather than the steep square law rate that conventional subwoofer drivers suffer. In short, the TRW retains its ability to actually couple to and drive the air, at progressively lower bass frequencies, far better than conventional subwoofers can.

Incidentally, as a technical aside, note that the radiation resistance and coupling strength would remain constant, and not decline at all, if a driver could increase its effective radius linearly with decreasing frequency, since such a driver's area would then be increasing as the square of frequency (the area of a circle is proportional to its radius squared), which would completely offset the square law decline dictated by the laws of physics for a fixed radius diaphragm. But the TRW fan only increases its area linearly with decreasing frequency, not its radius (its radius increases only as the square root of decreasing frequency), so it still suffers a modest decline in radiation resistance and coupling effectiveness at progressively lower bass frequencies. Still, a modest decline is a heck of a lot better than a steep decline. And thus this superiority in radiation resistance, in effective coupling to your room's air, marks yet another way in which the TRW is a far superior subwoofer than conventional subwoofers can possibly be.

D. Comparisons with Conventional Subwoofers in Bass Quality: Pressure

Electric fans in general, and the TRW fan in particular, are very effective at moving huge volumes of air, even at very low frequencies where conventional subwoofers lose their effectiveness (and indeed lose their claim to even be called true subwoofers), as discussed above. This effectiveness and ease, at moving huge volumes of air, is a key factor in the TRW's achievement of superb bass quality and waveform accuracy -- far superior to, and wholly different from, the inferior bass quality and waveform inaccuracies that conventional subwoofers are inherently constrained to and cursed by, due to their intrinsic nature (in other words, these inferiorities cannot be designed out of conventional subwoofers by better design engineering).

Furthermore, the fact that the TRW's effective radiating area gets huge at low bass frequencies also helps the TRW to achieve superior bass quality. That's because a driver with a huge radiating area can generate large volume airflow without resorting to high pressure. In contrast, conventional subwoofer drivers, whose radiating area does not increase at low bass frequencies, and whose radiating area is very small compared to acoustic wavelengths at low bass frequencies, must resort to creating high pressure, madly pumping their small diaphragms with high velocity and high excursion, in order to try to generate decent sound levels at low bass frequencies. Intuitively you can appreciate that a small piston pump must pump harder, with higher pressure, than a large piston pump, which can be much more relaxed, with lower pressure, to achieve the same total airflow volume.

There's a real physical difference between low pressure bass and high pressure bass, and you can hear (and feel) the difference. You can do a simple experiment to demonstrate this to yourself. Hold your open palm in front of and facing your mouth, about 3 inches away from your mouth. Now, let's simulate low pressure bass first. Relax your stomach diaphragm, open your mouth pretty wide (that's the large radiating area, like the TRW), and let a gentle, long "uhhhh" sound emerge from your stomach diaphragm (almost like letting out a belch). Feel the very gentle breeze on your palm, and listen to the relaxed ease of the "uhhhh" sound. Then, let's simulate high pressure bass. Purse your lips into a tight small circle (that's the small radiating area of a conventional subwoofer), and blow hard through this small opening. Feel how different the high pressure air feels as it hits your palm, from how the low pressure air felt. And listen to how the high pressure forced blow sounds so different from the low pressure relaxed "uhhhh".

Now, virtually all musical instruments generate low pressure bass, often employing large radiating diaphragms (bass viol, grand piano, bass drum) and/or large air volumes (pipe organ). When a conventional subwoofer, with its small driver diaphragm (small relative to the large acoustic wavelengths of low bass frequencies), tries to play this bass, it can only do so in a high velocity, high pressure, small volume mode.

That's the opposite kind of bass from the low velocity, low pressure, large volume bass that most musical instruments actually produce. It actually is physically wrong. And, as you just demonstrated to yourself, you can hear and feel the difference between these two opposite kinds of bass. So the wrong kind of bass produced by conventional subwoofers also audibly sounds wrong and feels wrong. Deep bass from conventional subwoofers sounds just like what it is, a small piston madly flailing away at the air with high pressure.

In contrast, as we've just learned, the TRW intrinsically, automatically, and effortlessly increases its effective diaphragm area and its volume of airflow per signal cycle at low bass frequencies. Since the TRW is automatically blessed with a huge diaphragm at low bass frequencies, and can move huge volumes of air per signal cycle at low bass frequencies, it intrinsically, automatically, and effortlessly emulates the same basic mechanisms for producing bass that musical instruments employ, large diaphragms and large air volumes. And, being blessed with a huge diaphragm and large volume airflow at low bass frequencies, the TRW does not have to resort to forced high pressure, any more than musical instruments themselves do. Since the TRW reproduces low bass with the same basic properties as musical instruments themselves do (large diaphragm, large volume, low pressure), the quality of its bass sounds right and feels right (more sonic details later). The TRW's bass, like that of most musical instruments, has an authoritative, massive, relaxed ease, much like the "uhhhh" that came from your relaxed, large stomach diaphragm through the large opening of your wide open mouth. A large area diaphragm that can move large air volume can afford to be relaxed in its efforts, whereas a small piston diaphragm has to be work hard with a forced quality.

You can simulate this contrast with a simple modification of the above experiment. To simulate the frenetic, forced, high pressure in-out pumping, by a conventional subwoofer's small area diaphragm, try panting hard and fast, in and out, forcing the air at high pressure through the same small mouth opening, with your lips tightly pursed into a small circle, and using your cheek muscles to push the air out. To simulate the relaxed ease and low pressure of the TRW's diaphragm, with its large area at low bass frequencies, gently wafting large volumes of air back and forth, try letting your mouth hang wide open, relax your stomach and mouth muscles, and do deep, relaxed, slow breathing in and out, using your stomach diaphragm muscles, and letting the large volumes of air flow gently out by simply relaxing your stomach diaphragm muscles (you don't need to blow air out at all, since it just naturally comes out when you relax your stomach diaphragm muscle, and indeed the only time your stomach diaphragm muscle even works at all is to expand your air intake when you breathe in).

E. Comparisons with Conventional Subwoofers in Bass Quality: Bass Response

Another key factor determining bass quality and accuracy is the low frequency response of a subwoofer, as seen in both the frequency and time domains.

Electric fans in general, and the TRW fan in particular, also are inherently excellent in their capabilities at very low frequencies, indeed all the way down to zero Hz (DC). In fact, conventional fans are intrinsically pure DC devices, continually blowing a constant amount of air in one direction. It actually takes some design work to change this intrinsically DC device into an AC device, as the TRW does by engineering in the feature of variable pitch blades. Thus, it should come as no surprise that fans in general, and the TRW fan in particular, intrinsically has perfect response, in both the frequency and time domains, at very low bass frequencies, down to and including DC. The fan is thus an ideal technology for making a true subwoofer.

This is in complete contrast and opposition to conventional subwoofer drivers, which inherently run into great difficulties trying to reproduce lower bass frequencies. Conventional cone drivers are intrinsically AC devices, and are great for reproducing middle frequencies, but they suffer worse and worse physical handicaps and outright roadblocks, in many distinct ways, as the frequencies get into the bass region, so that by 40 Hz they have pretty much reached the limits of their effectiveness, and they can cover the single 20-40 Hz octave only with poor quality and with severe difficulty, and for the infinity of octaves below 20 Hz they are virtually useless (whereas the TRW covers this infinite octave span perfectly). So cone driver technology is simply not appropriate for frequencies below 40 Hz, which means it should never have been employed in the first place for making true subwoofers.

Of course, the reason that cone driver technology was stretched into subwoofer bass territory was that it was and is the predominant driver technology available, so it was the most convenient choice. But subwoofer systems made with cone drivers are actually poor excuses for subwoofers, and don't even deserve to be called subwoofers, because of these physical handicaps and outright roadblocks cone drivers face at low frequencies. Because of their intrinsic nature, they inherently cannot possibly produce high quality bass.

You're probably already familiar with most of these physical handicaps and outright roadblocks that cone drivers face at low frequencies, and some have already been mentioned above. Here, we'll show how these physical handicaps and roadblocks adversely affect specific key aspects, of the quality of bass that conventional subwoofers can produce. And then of course we'll show how the TRW is completely free of these physical handicaps and roadblocks, so it can produce far, far better quality bass in these same specific aspects.

E.1. Amplitude Frequency Response

First, let's discuss the several distinct handicaps and roadblocks affecting amplitude frequency response, especially at low bass frequencies (precisely the frequencies which it is a subwoofer's primary job to cover well). The excursion of a cone driver approximately quadruples for every halving of frequency, when playing the same loudness level, so cone drivers soon run out of excursion capability as the bass frequency goes lower, even at modest bass energy levels, which means that a cone driver cannot extend to low bass frequencies at any reasonable energy level, even if it were made to have flat frequency response to yet lower bass frequencies. Because of their poor amplitude frequency response at low bass frequencies, conventional subwoofers cannot produce high quality bass, and their low quality bass will lack the correct impact (that kick you feel in your stomach from live bass).

Then, even before a cone driver runs into the abrupt roadblock of its excursion ceiling, it is handicapped by worsening distortion (hence degraded bass quality) at higher excursions, plus thermal limits at higher loudness levels. And, if a cone driver is constructed to have lower distortion at large excursions, say via an overhanging voice coil, it thereby acquires poorer efficiency, which means that it will run into its own thermal limitations sooner (and power amplifier limitations sooner). These further handicaps can also adversely affect bass quality, perhaps indirectly.

Furthermore, cone drivers also have a resonance frequency at the bass end of their range, and their frequency response declines steeply below this frequency, so this frequency marks a roadblock, the lowest bass frequency that they can play effectively. And, attempts to change this resonance to a lower frequency, say by making the woofer cone heavier, degrade efficiency, again meaning that the driver will run into its own thermal limitations sooner (and power amplifier limitations sooner).

In contrast and opposition, the TRW subwoofer does not face any of these handicaps or roadblocks. The TRW happily and effortlessly plays lower and lower bass frequencies, without any limit, even down to DC, and (as discussed above) its performance in some ways gets even better at lower and lower bass frequencies. Moreover, the TRW can play these arbitrarily low bass frequencies at bass energy (loudness) levels far greater than conventional subwoofers can. So the TRW, with its amplitude frequency response down to DC, plays very high quality bass (in a whole different league from conventional subwoofers), with full and accurate impact and kick, just like you hear from live bass.

E.2. Phase Frequency Response

Second, let's discuss a cone driver's handicaps and roadblocks that affect the phase of its frequency response, especially at low bass frequencies (precisely the frequencies which it is a subwoofer's primary job to cover well). A cone woofer's low frequency resonance is a phenomenon based on high reactances interacting, the equivalents of inductance and capacitance. These reactances store energy, and they drastically shift phase. Drastically shifting the phase in turn drastically alters the audio signal waveform, so the reproduced acoustic waveform is not at all an accurate replica of the input electrical waveform.

To make matters worse, these reactances at the woofer's resonant frequency still shift the phase at much higher frequencies than the resonant frequency. At these higher frequencies the subwoofer is putting out its full energy, and then soon starts to blend with the woofer of the main loudspeaker system (since a subwoofer's spectral coverage spans only a couple of octaves). But, since the subwoofer's waveform is drastically altered by phase shift, its acoustic waveform can't add correctly to the acoustic waveform from the main loudspeaker's woofer, so the summed acoustic result will be wrong, and you'll be getting poor quality, inaccurate bass.

This reactive phase shift error is very bad at the resonance frequency, and further degrades the bass quality that might already be ruined by any amplitude irregularities at resonance. And this reactive phase shift error then continues below the resonant frequency, where the woofer's amplitude response is steeply rolling off.

Conventional subwoofer systems employ various distinct enclosure designs, and these enclosure designs impose even worse phase shift errors. Indeed, the enclosure designs (e.g. vented) that do best at extending the flat amplitude response to the lowest possible frequency, and which are often employed for this very reason, are the worst at worsening errors in the system the phase response. These enclosure designs might do best at extending the flat amplitude response, but then they have the steepest rolloff slope for all bass frequencies below resonance, and steeper slopes always mean worse phase shift errors. Likewise, the shape of the corner of the amplitude response curve, at resonance, plays a role in how bad the phase shift errors are. Somewhat higher Q bass enclosure alignments might produce flatter, more extended amplitude response, and are often employed for this very reason, but they have sharper corners in their amplitude response curve at resonance, so they also produce worse phase shift errors. As you can see, the conventional subwoofer is necessarily compromised, being damned if it does and damned if it doesn't, since it faces a compromising tradeoff: going for flatter, more extended amplitude frequency response necessarily brings worse errors in phase frequency response.

In contrast, the TRW subwoofer simply has no reactance at all, at low bass frequencies. So the TRW inherently has perfect amplitude frequency response, without any resonances, rolloffs, or limits to its very low frequency extension. Likewise, with no reactance, the TRW inherently has no phase shift at low bass frequencies. So the TRW intrinsically puts out virtually perfect waveform fidelity, for adding to your main loudspeaker and creating an accurate summed audio waveform from your system. And the TRW does not face any of those compromises that conventional subwoofers necessarily face, for example, the TRW does not have to trade off bass extension of its flat amplitude response against worsening phase errors. The TRW inherently has infinitely extended amplitude response, down to and including DC, and infinitely extended phase response, down to and including DC, without phase errors.

E.3. Time Domain Response

Third, let's discuss a cone driver's handicaps and roadblocks that affect its time domain response, especially at low bass frequencies (precisely the frequencies which it is a subwoofer's primary job to cover well). It's worth noting that time is a physically real entity of the universe, indeed a dimension of the universe, whereas frequency is merely an abstract concept, a convenient artifice invented by humans. Thus, actual acoustical events, and the signals we use to represent them, actually take place in time domain, as time moves forward and the event or signal moves forward, and they do not take place in the frequency domain (not in the same primary sense, but only in an abstract conceptual derivative sense). Likewise, actual loudspeaker diaphragm and radiation events, in other words actual loudspeaker performance, happen in the time domain, as time moves forward, not in the frequency domain. And our ear/brain perceives these loudspeaker diaphragm and radiation events in the time domain, as they take place, not in the frequency domain. The frequency domain might be useful, commonly used tool for retroactively summarizing and abstractly conceptualizing a loudspeaker's performance, especially for design and engineering purposes. But the frequency domain is not the domain in which the loudspeaker's performance actually happens, nor the domain in which we actually perceive the loudspeaker's performance happening. That privilege is reserved for the time domain.

Thus, the time domain response of a loudspeaker is arguably more important than any of the frequency responses (amplitude or phase), because signals themselves occur in the time domain, because the loudspeaker performance actually occurs in the time domain, and because the ear/brain hears these signals in the time domain. Also, the brain interprets and analyzes these heard signals in the time domain (especially at low frequencies, where the time domain waveform evolves more slowly, so the brain has plenty of time to interpret and analyze what the evolving waveform pattern sounds like and means, as it evolves in the time domain).

E.3.a. Inverse Relationship of Time and Frequency

Now, it so happens that the abstract concept of frequency was invented to be the mirror inverse of time. So the abstract frequency domain is by definition the mirror inverse of the real, concrete time domain. This means that a loudspeaker's performance as characterized in one of these domains is related to, and indeed is the mirror inverse of, its performance as characterized in the other domain. For example, if we have characterized a loudspeaker's performance completely in the frequency domain (including both its amplitude frequency response and its phase frequency response), then we can thereby also predict what its performance will actually be in real time, i.e. in the time domain.

Thus, the many physical handicaps and roadblocks that conventional subwoofer drivers face, which mess up the conventional subwoofer's performance as abstractly characterized in the frequency domain (via both amplitude and phase errors), as discussed above, also mess up the conventional subwoofer's actual concrete behavior in real time, in the time domain. The actual signal waveform produced by conventional subwoofers is a total mess.

And an educated ear can easily hear what an ugly mess it in fact is. Moreover, even someone with an uneducated ear can instantly hear what a mess it is, if he merely hears it directly compared to the signal waveform from the TRW. It is night and day.

There is a standard test signal which is used to directly test devices' performance in the time domain, called the step signal. This signal waveform looks just like a single step (of say a stairway). This step signal starts out at 0 level, then instantly (vertically) transitions to some higher level, and then stays flat at that higher level, for an indefinitely long period of time. This step is actually the simplest possible test signal, since it consists of just one single transition, and just two signal levels, to be reproduced. But it is very hard for any device to reproduce accurately even this simplest possible test signal, and most devices fail to do this rather miserably, especially conventional subwoofers.

The actual performance of the device under test, as it actually happens in the time domain, in reproducing this test signal accurately or poorly, can be easily and directly viewed on a storage oscilloscope. Specific types of actual time domain waveform errors, made by the device in trying to reproduce this simplest test signal, can be visually interpreted, and can be correlated with specific shortcomings or failures in the device. Additionally, they can also be correlated with shortcomings as seen in the frequency domain.

Since the concept of frequency was invented to be the mirror inverse of the real phenomenon (and dimension) of time, a simple inverse relationship holds between a device's performance as viewed indirectly in the frequency domain, and that same performance as viewed directly in the time domain. Performance errors that occur sooner in time, with a smaller amount of time elapsed, correlate with the inverse, a larger or higher frequency. And performance errors that occur later, with a larger amount of time elapsed, correlate with the inverse, a smaller or lower frequency.

If you feel mentally disoriented from this inverse talk, it might help to think of this inverse relationship in a practical rather than merely a conceptual manner. If a device, say a loudspeaker, is cycling back and forth faster, each cycle obviously takes a smaller amount of time, but of course this means that there are more cycles per second occurring, and cycles per second is another word for frequency. Presto! Smaller amount of time is equivalent to larger frequency, an inverse relationship. Also, note that any errors committed by this faster cycling loudspeaker would have to be committed sooner, within its now shorter cycle period (presumably this same error would then be repeated each signal cycle), which means that an error at a higher (larger) frequency has to show up sooner, after a smaller amount of time, in the time domain waveform. Conversely, if a device, say a loudspeaker, is cycling back and forth slower, each cycle obviously takes a larger amount of time, but of course this means that there are less cycles per second occurring, and cycles per second is another word for frequency. Presto! Larger amount of time is equivalent to smaller frequency, an inverse relationship. Also, note that any errors committed by this slower cycling loudspeaker can be committed later, within its now longer cycle period, which means that an error at a lower (smaller) frequency can show up later, after a longer amount of time, in the time domain waveform.

This inverse relationship means that, to examine and interpret a subwoofer's accuracy, at the low frequencies where it operates, we should look at the later (longer time) portions of its response to the standard step test signal. Because subwoofers do not reproduce large (high) frequencies, the beginning (small, low time period) portion of its reproduced step signal will fail to have an instant risetime, and will instead rise slowly. But that's perfectly fine. What we want to look at is a subwoofer's time domain response, in trying to reproduce this step test signal, later in time, i.e. after a higher period of time, since (thanks to the inverse relationship) this higher period of time shows the subwoofer's capabilities at lower frequencies, precisely the low bass frequencies where every subwoofer should be accurate.

So, with the above discussion as preface, let's look at, and interpret, the time domain response of conventional subwoofers.

E.3.b. Conventional Subwoofer Region 1, Premature Decline

The test input signal, a step, rises to some higher level above zero, and then stays at that same higher level indefinitely. But a conventional subwoofer's output signal fails to stay at that higher level indefinitely. Instead, a conventional subwoofer's output signal begins declining back down toward zero, much too soon, in the first region of its time domain response to the standard step test signal input. This too-soon declining means that a subwoofer robs all bass transients of their true full impact. All bass transients, be they bass drums or cannon shots or synthesized sound effects, depend, for their massive impact and weight, not only upon their loud initial level but also upon their duration in time. To see that this is so, consider as a reductio a signal that rises to full strength but then very quickly declines; it is known as an impulse, and it sounds like a mere tick, with no sonic weight or impact, simply because it lacks duration. Conventional subwoofers, by declining too quickly, wimp out before bass transients can convey their true, full impact and weight to you.

Incidentally, this time domain error of conventional subwoofers, wimping out from full level too soon, and not lasting at full level for a high enough time period happens to correlate with a frequency domain error discussed above, wimping out from full amplitude level at too high a frequency, and not lasting (extending) at full level to a low enough frequency, i.e. rolling off in the low bass, below system resonance (note again the inverse relationship, in that failing to last at full level for a high enough time period correlates with failing to last at full level (extend) to a low enough frequency). But, when playing real music and films, with their real bass transients, it is the time domain premature declining error that we directly hear, while the corollary frequency response rolloff relates instead to steady tone sine wave frequency domain measurements, and to a few steady tone bass sounds (like pipe organs). Thus, for most music and most sound effects, it is the time domain error that is more significant than the corollary frequency domain error. And this fact, the predominance of time domain error, will become crucial when we later consider the limits of low bass that humans can hear and that real sounds produce.

E.3.c. Conventional Subwoofer Region 2, Negative Overshoot

The second huge error that conventional subwoofers make, in their time domain performance, is overshoot below the zero axis (representing zero output signal level). After conventional subwoofers decline too soon from full level, they then commit a further blunder, in region 2 of their time domain response to the standard step test signal input. Instead of simply approaching the zero signal level axis, and settling down to zero signal level, they actually continue downward, overshooting below the zero signal level axis, and then they start putting out a negative signal.

This negative signal output creates acoustic energy in the wrong direction, sucking instead of pushing. In effect, the conventional subwoofer changes its mind, and sucks back in some of the air, and some of the bass energy, that it had just previously put out.

E.3.c.i. Sucking vs. Pushing in Conventional Subwoofers

As you can intuitively see, this overshoot error compounds the felony previously committed by the conventional subwoofer in wimping out too soon from full level. When the conventional subwoofer wimped out too soon, it robbed some of the true impact and weight from every bass transient. Now, by overshooting below the zero axis, and sucking back in some of the already-too-little bass energy it had just put out, the conventional subwoofer is reducing even further the impact and weight of each and every bass transient. Remember that the input test signal, a step, contains only positive pushing bass energy, so when the conventional subwoofer outputs negative sucking bass energy in its erroneous response to the input test signal, this is a major, major blunder. Note also that the standard step test signal, even though an artificial signal, does honestly represent and probe the bass reproduction requirements for actual bass transients, both musical and sound effects (as we'll discuss further below).

The human ear/brain is a superb time domain analyzer in general, and here in particular is very good at two pertinent evaluation techniques, integrating bass energy over time, and performing a time slicing analysis of the bass waveform as it is output by a conventional subwoofer.

As the ear/brain performs the first evaluation technique, integrating the bass energy over time, the negative sucking in by the conventional subwoofer's negative overshoot, even though occurring at a later time than the conventional subwoofer's initial positive foray, becomes integrated with that immediately preceding positive foray, and thus literally subtracts bass impact energy and weight away from the already-too-little amount in that preceding positive foray. In effect, the positive pushing bass energy sensed by the ear/brain over time, as the total positive area under the waveform curve, is lessened by the negative area under the negative overshoot portion of the conventional subwoofer's time domain response curve.

The second evaluation technique, the time slicing analysis ability of the ear/brain, also comes into play here. The ear/brain is very good at being able to tell when a waveform of a familiar sound has the wrong polarity, and is thereby sucking air instead of pushing air. For example, in the spectral midrange we are very good at hearing when a trumpet or vocalist is sucking instead of pushing air, because it simply sounds wrong, since trumpets always push and never suck, as do singers when enunciating words (try saying or singing words yourself, while inhaling instead of normally exhaling, and note how different and absurdly wrong it sounds). Similarly, a trained or sensitive listener can tell when part of the bass waveform, put out by a conventional subwoofer, is suddenly sucking instead of pushing air, on what should still be the positive pushing impact portion of a bass transient. That especially true when the ear/brain, with its time slicing analysis capability, has just heard, for immediate direct comparison, part of the same bass transient sound put out in correct positive pushing polarity. The ear/brain hears this sucking blunder as making the bass transient puffy and hollow in quality, like a soft cotton ball, instead of being the solid hard impact punch to the stomach that an accurate bass transient, with only positive pushing, would be.

E.3.c.ii. Compressed Dynamics by Conventional Subwoofers

This negative overshoot blunder by conventional subwoofers also engenders further losses of sonic quality, which may be the worst of all (depending on program material). It can reduce (compress) dynamics, and can cause sonic confusion, even outright distortion, of the program content that immediately follows a bass transient. How does this happen?

First, let's discuss the dynamic compression, of the program content following a bass transient. Recall that our standard step test signal goes positive and stays positive, so the ideal subwoofer, to be correct, should only put out positive pushing airflow and pressure. But every conventional subwoofer spontaneously misbehaves and goes negative on its own, during this second region of its time domain response, sucking air back in even while the input signal is still at full positive level, and is thereby still instructing the subwoofer to keep pushing air out. Moreover, this misbehaving conventional subwoofer executes this entire negative sucking portion of its output on its own time schedule, without paying any attention to the input signal (as proven by the fact that it ignored the step input signal's command to stay positive).

Now, our standard step test signal consists of one single signal transition, with no further signal change after that, so it is in effect a single bass transient. But, in all real program material, a single bass transient is followed by other program information, hence further new signal changes. These further new signal changes could be a second distinct bass transient, or they could be a midrange or treble transient, or they could be a positive going half cycle of say a bass drum note that continues after the initial whack. Whatever these further new signal changes are, they are sure to contain some positive polarity waveform information, i.e. some instruction to increase the positive pushing airflow and pressure in your room and hence at your ear, perhaps from your main loudspeaker (if in the midrange or treble), or perhaps from the subwoofer itself.

However, whatever the specifics of this new instruction to increase the positive pushing airflow and pressure in your room and at your ear, the conventional subwoofer will simultaneously still be in its negative sucking second region of time domain response, from the earlier original bass transient. Thus, the conventional subwoofer will still be negatively sucking (decreasing) airflow and pressure out of the room and out of your ear, even as the new program information instructs the airflow and pressure to be positively pushed (increased) into the room and into your ear. The obvious consequence is that the conventional subwoofer, during its period of negative sucking spurious misbehavior, will subtract from the positive dynamic peak of positive pushing airflow and pressure commanded by the new signal. In short, the negative overshoot blunder by conventional subwoofers reduces the dynamics of succeeding new positive signal waveforms in the program that happen to arrive during the second region of the conventional subwoofer's misbehaving time domain response.

If the succeeding new signal waveform represents a second positive pushing bass transient, to be reproduced by the subwoofer, its dynamics will be compressed and reduced by the negative sucking that the misbehaving conventional subwoofer is executing at the same time. If the succeeding new signal waveform represents the positive pushing of a bass drum head as it continues to sound after the initial whack, that too will have its dynamics compressed and reduced. And, even if the succeeding new signal waveform represents a positive push from some musical instrument or other sound source in the midrange or treble, to be reproduced wholly by your main loudspeaker and not by the subwoofer at all, the subwoofer's negative sucking misbehavior will still compress and reduce its dynamics, since the subwoofer will be reducing and sucking air pressure out of the room even as the main loudspeaker is trying to push and build up air pressure into the room, and since all you get to hear at your listening seat is the net air pressure change in the room.

E.3.c.iii. Sonic Confusion Caused by Conventional Subwoofers

This negative overshoot blunder by the conventional subwoofer also causes sonic confusion, that extends far beyond its own butchering of the sonic quality of the initial, original bass transient. The bass drum doesn't sound right when its positive pushing excursions are attenuated, and the midrange or treble transients from your main loudspeaker don't sound right when their positive pushing efforts are attenuated. Moreover, the misbehaving subwoofer actually creates a kind of even order distortion, for all music and all sounds, which happen to occur during this second region, of negative overshoot misbehavior, in its time domain response. The negative signal pressure, spuriously created by the misbehaving subwoofer, will act as an acoustic signal bias on all other program signals that happen to occur during the time period of this second region, reducing the positive going peaks and increasing the negative going peaks. That simply amounts to even order distortion, and should degrade the overall sound in much the same way that an amplifier with excessive even order distortion would.

E.3.c.iv. Worst Negative Overshoot Offenders among Conventional Subwoofers

Which conventional subwoofers commit this negative overshoot blunder, on all bass transients? They all do. The only conventional woofer or subwoofer which could elude this blunder would be a system whose bass rolloff is very shallow, at 6 dB per octave or less. But there are no such systems among conventional woofers or subwoofers. Dipole woofers have a small part of their spectral range which does roll off at merely 6 dB per octave, so for this narrow spectral region they can have somewhat better bass transient response, with at least no negative overshoot for a little while (temporally). But even they, for every bass transient, commit the blunder of negative overshoot later in time, when, at a lower bass frequency than the dipole rolloff corner, their actual driver encounters its own free field resonance, and then begins rolling off below that resonance frequency at a steeper 12 dB per octave slope, which engenders the negative overshoot blunder. All conventional woofers and subwoofers in infinite baffle enclosures commit this negative overshoot blunder, since they all have rolloff slopes of 12 dB per octave. And all woofers and subwoofers in vented bass enclosures also commit this negative overshoot blunder, generally to an even worse degree, since they have even steeper rolloff slopes, of 24 dB per octave or higher.

This blunder of negative overshoot in the time domain performance can also be correlated with performance errors as viewed in the frequency domain. In this case it is the phase frequency response (rather than the amplitude frequency response) that primarily shows the error. All conventional subwoofers have large reactance, and a low frequency resonance, within their spectral range, and this large reactance causes severe phase errors, near and below the resonance frequency, as noted above. When these phase errors exceed 90 degrees, the actual performance of the conventional subwoofer, as seen and actually heard in the time domain, goes negative and starts sucking air in instead of staying positive and continuing to push air out, for what should still be the positive portion of the output, since the input step signal is still fully positive (note that this is not a sine wave input signal, which does go negative after a while, so the subwoofer has no excuse at all for going negative). As the phase error continues to get larger, toward 180 degrees, the conventional subwoofer's actual output, as seen and actually heard in the time domain, goes farther and farther negative, sucking in air even more strongly, and thereby effectively canceling out even further (so far as the ear/brain's integrating ability is concerned) the previous positive push of air.

E.3.c.v. Irony of Misguided Design Goals in Conventional Subwoofers

There's a bitter irony here, involving misguided design goals of many engineers, perhaps driven by their marketing departments. Conventional subwoofer drivers are put into sealed enclosures in order to extend their flat amplitude frequency response down to lower frequencies. They thereby look better at passing the test of reproducing steady tones like test sine waves (so their amplitude frequency response looks better, more extended, on paper). And they thereby also get better at playing steady bass tones, like organ notes, with full flat response down to lower bass frequencies. Furthermore, the sealed enclosures of conventional subwoofers are often opened with a vent (or port, or passive radiator), in order to extend their flat amplitude frequency response to yet lower frequencies, so they look even better on paper and are even better at playing steady bass tones like organ notes. But these various enclosures, which make the amplitude frequency response look better for steady tones, also thereby make the phase frequency response errors worse. The reactive components of the steeper rolloff slope below resonance, and of the sharper corner at resonance, as seen in the amplitude frequency response curve, make the phase frequency response errors worse.

And here's the kicker. These worsened phase response errors also make the time domain response worse, specifically making the blunder of negative overshoot larger in magnitude and larger in area and longer lasting in time. This makes the subwoofer negatively suck in more air, thereby canceling more of the positive push bass energy it just generated. In short, it worsens the time domain response of the subwoofer. And remember, the time domain response shows the actual performance of the subwoofer as it happens in real time, which is also the way that your ear/brain hears it, in real time. Thus, the very same measures that are popularly (indeed almost universally) employed to make the conventional subwoofer look better on paper, in its amplitude response bass extension for steady tones (test sine waves or organ notes), ironically make the subwoofer's actual performance in the time domain worse.

This irony is especially relevant to all bass transients. The sonic quality of all bass transients is intimately dependent on the quality of a subwoofer's time domain response. We've just seen above that the sonic quality of bass transients degrades when conventional subwoofers decline too soon in their bass transient response, their time domain response to a step test signal input, with the bass sonic quality becoming wimpy by losing massive impact and weight. And we've also just seen that the sonic quality of bass transients degrades when conventional subwoofers go negative, and start negatively sucking in air when they should still be positively pushing out air, making the bass quality of bass transients puffy and hollow instead of solid.

Now, the vast majority of bass you get from all recordings consists of bass transients, not steady bass tones. Virtually all musical notes, and virtually all film sound effects, are changing over time, so they are transients, which have a start, a peak, and then soon an end (if they didn't, they would be playing unchanged for a long time). So virtually all sounds have a bass transient component (we'll discuss this further below). In contrast, very few bass events are steady tones (such as sustained notes from an organ, or background atmospheric film sound effects). In everything your hear, bass transients outnumber steady bass tones over 1000:1. So it's bitterly ironic that, with conventional subwoofers, the very design measures, employed to improve bass extension for the 1 steady bass tone, actually make bass performance worse for the 1000 bass transients, with a wimpy loss of bass impact and weight, and a loss of solidity as the bass sonic quality becomes puffy and hollow, and compression of system dynamics, with sonic confusion and even order distortion.

E.3.d. Conventional Subwoofer Region 3, Ringing

We've just looked at two regions of the time domain response where conventional subwoofers have major failings, the first being a too quick decline of positive pushing bass energy, and the second being a negative sucking region that works to effectively cancel some of the already-too-little positive bass energy just previously pushed out. There's also a third region of the time domain response, where most conventional subwoofers also commit major blunders. And this third region also has dire, adverse sonic consequences.

At some point in the time domain response, a conventional subwoofer's negative overshoot is finished, and its response goes back up toward the zero axis (representing zero output signal level). What does the conventional subwoofer do now?

A few conventional subwoofer systems, those in sealed enclosures with a low Q (critically damped or better) alignment design, approach the zero axis from below, and then do not rise again above the zero axis. These few conventional subwoofer systems still commit the blunders in the first two regions of their time domain response as discussed above, so they still suffer the degradations of bass sonic quality discussed above, but at least they do not commit further errors in this third region of time domain response, and so they do not also suffer the further degradations of bass sonic quality to now be discussed. But the vast majority of subwoofers with sealed enclosures try for maximally flat, maximally extended amplitude response, which means a sharper corner in their amplitude frequency response near resonance, which means a higher Q, which means that they do also misbehave in this third region of time domain response, going back above the zero axis after their negative overshoot period is finished.

Then, all conventional subwoofers with vented enclosures commit blunders in this third region. And some vented bass designs are worse than others. Generally speaking, those vented bass alignment designs that strive to extend their flat amplitude frequency response the farthest, to the lowest bass frequency, commit the worst blunders in their actual time domain behavior, especially in this third region, and therefore sound the worst on all bass transients.

This again correlates with the phase errors of these various conventional subwoofers, as seen in their phase frequency response. These maximally extended vented bass designs have the steepest rolloff slopes, and that portends the worst phase errors, reaching the highest amount of phase rotation. With a step test input signal, the starting point in the time domain is the full level of the step (and an ideal subwoofer would simply stay at that full level). Thus, when a conventional subwoofer's phase error reaches 90 degrees, it will have prematurely finished its first positive excursion, and will be back down at the zero signal axis, about to go negative for phase errors above 90 degrees. Then, when a conventional subwoofer's phase error reaches 270 degrees, it will have finished its unwarranted negative excursion, and once again be back up at the zero axis. Since the phase error of all vented subwoofers (and most sealed box subwoofers) exceeds 270 degrees, their time domain response behavior will not stop at the zero axis after their negative overshoot, but instead will once again go positive, above the zero axis. And, if a vented subwoofer's phase error exceeds 550 degrees (thanks to its steep rolloff slope and sharp, high Q corner), then it will again go negative, later in its actual time behavior, as you will actually hear it, and as we can see in its time domain response to the standard step test signal.

When a conventional subwoofer goes back up across the zero axis in its time domain behavior, after it has completed its negative overshoot, this becomes known as ringing. This appellation makes good sense. This conventional subwoofer has completed in effect one full cycle, first a complete positive excursion and then a complete negative excursion (like two half cycles). If the conventional subwoofer continues to output energy after it has in effect completed one full cycle, then it is ringing, i.e. continuing to cycle even after one cycle has been completed.

Remember that the standard step test input signal has only one single voltage transition, and then stays fixed at a constant voltage level. So all this back and forth cycling, this ringing, seen in the output of a conventional subwoofer, in response to this simple single voltage transition as the input signal, is totally unwarranted, and represents totally spurious garbage output by the conventional subwoofer.

E.3.e. Further Sonic Problems from Conventional Subwoofer Ringing

Many further sonic problems are caused by this ringing, spurious garbage output, emitted by conventional subwoofers.

E.3.e.i. Lingering Overhang from Conventional Subwoofers

First, there is a lingering overhang, making bass transients sound slow, heavy, and soggy, with poor definition. The conventional subwoofer's spurious ringing has an approximate periodicity, and the human ear/brain, with its time windowing analysis capability, interprets this ongoing periodic ringing as though it were a separate bass tone, lingering after the original attack of the bass transient. Remember that the input signal consists here of just one single transition, which obviously does not linger in time, so there should not be any lingering AC signal at all by the subwoofer. And note that the conventional subwoofer's spurious ringing would likewise continue after every bass transient attack, just as it continues after this single signal transition by or step test signal.

The sonic artificiality of this lingering, heavy bass overhang is especially noticeable to humans, hence especially obnoxious, because its cycling periodicity occurs over a moderately long time span that is typically beyond the Haas window of 10 to 15 milliseconds. When two sounds occur together, or separately but within the Haas time window, the brain tends to fuse them together so they coalesce into one perceived sound. But, if the second sound occurs after the first by a time period longer than the 10 to 15 millisecond Haas time window, then the brain hears them each as a distinct sound. Thus, with this lingering tail of spurious cycling, by conventional subwoofers, taking place and lasting beyond the 10 to 15 millisecond Haas time window, the brain hears the lingering overhang as a distinct sound, and thereby pays more attention to it, and of course recognizes it as a totally foreign sound.

Incidentally, when audiophiles and designers speak of a woofer sounding fast or slow, they are actually addressing not the woofer's attack risetime, but rather this phenomenon of its lingering overhang, hence its slow decay. Woofer systems with a heavier, longer lasting decay (often due to this spurious ringing) sound heavier and slower, whereas woofer systems that decay faster and do not have a prolonged spurious ringing sound faster.

There's a technical irony here. A conventional subwoofer's perceived slowness, its lingering overhang and ringing on the decay side of transients, is caused not by its inability to reach ***high*** enough in frequency extension (i.e. to be fast enough), as one might suppose, but rather is actually caused by its inability to go ***low*** enough in frequency extension, such that it converts incoming energy below its bass cutoff frequency into its own AC overshoot and ringing pattern, which temporally lingers with an overhang. If this conventional subwoofer could somehow magically extend far ***lower*** in frequency response, as low as the incoming signal's spectral content, then it could accurately obey and track this input signal, and would accurately reproduce the input signal's decay, and would not generate its own spurious, lingering AC ringing (slow-sounding overhang), and thus would sound ***faster***. Of course, such a magical subwoofer does now exist, the TRW.

E.3.e.ii. System Transparency Loss from Conventional Subwoofers

The second sonic problem is that this prolonged spurious AC ringing is an AC signal that competes with and thereby obscures new, succeeding program information that comes along, at all frequencies. Thus, a conventional subwoofer with this lingering overhang makes your system less transparent.

Simply put, the loud sound from the conventional subwoofer's periodic ringing blocks and obscures the more delicate, subtle sounds that your main loudspeakers are putting out, which prevents you from hearing those subtle sounds, and which thereby degrades the perceived transparency of your system as a whole.

And this obscuration continues for a long time, so long as the conventional subwoofer keeps ringing in its misbehaving response to the original earlier bass transient. Indeed, if there is a repeating bass transient rhythm or ostinato, the misbehaving conventional subwoofer might well be ringing virtually all the time, so the rest of the sound might be partially obscured virtually all the time.

E.3.e.iii. One-Note Boom from Conventional Subwoofers

The third sonic problem is that the ear/brain hears the cycling periodicity of the conventional subwoofer's ringing, and reasonably interprets this cycling periodicity as an ongoing, lingering bass tone or note, at a frequency corresponding to the cycling periodicity. Thus, the ear/brain hears the conventional subwoofer's ongoing ringing as a one-note boom. The periodicity of this cycling misbehavior is dictated by the physical parameters of the conventional subwoofer, such as its various reactances, phase errors, etc. So the periodicity of this cycling ringing always stays the same, for every bass transient, even though the sound of distinct bass transients might itself be different and changing.

For example, as a plucked jazz bass viol goes up and down the musical scale, the pitch of its transient bass notes keeps changing. But the perceived pitch of the conventional subwoofer's ringing hangover, as repeatedly triggered by these different bass transients, stays the same, because the periodicity pattern of its misbehaving ringing, dictated by the subwoofer's own physical parameters, stays the same. Hence, this conventional subwoofer will continue to strongly play the same bass note with its booming, ringing, lingering overhang, in the immediate shadow of each pluck of the jazz bass viol goes up and down the musical scale to differing bass notes. The one-note boom from the conventional subwoofer obscures the varying bass notes actually being input to the subwoofer from the plucked bass viol.

Incidentally, because this strong one-note boom is always at the same frequency, it sounds just as if the loudspeaker has a sharp peak in its amplitude frequency response at this frequency, with extra energy at this frequency, plus the prolonged ringing that is the natural consequence of a sharp peak in amplitude frequency response. But in fact there is no peak at all in the amplitude frequency response at this frequency. The very real sonic problem, the one-note boom, that is so awfully audible, is totally hidden and undiscoverable from the amplitude frequency response. But it is very clearly revealed in the time domain response. This is yet another example where the time domain response, which shows the actual concrete behavior of the loudspeaker in real time, is more important, and more relevant to how the loudspeaker actually sounds in real time, than the amplitude frequency response, which shows only an abstract conceptual summary, and a summary at that of only one aspect of the loudspeaker's frequency domain capabilities (it ignores the phase frequency response error aspect).

E.3.e.iv. FM Distortion of Full Spectrum by Conventional Subwoofers

An interesting fourth sonic problem is that the AC signal, represented by the spurious ringing of the misbehaving conventional subwoofer, creates sidebands around every musical note, every vocal sound, every sound effect - even those in the midrange and treble spectral regions. Because the subwoofer is putting out high acoustic energy, its spurious, misbehaving ringing strongly modulates the air pressure in the room that represents all the rest of the program. Moreover, this modulation is the worst kind of modulation, Doppler or FM distortion, which Klipsch has shown to be far more audibly obnoxious than other kinds of distortion (e.g. AM distortion), even in small amounts. The human ear is inherently nonlinear, so it acts as a detector or demodulator of these FM distortion sidebands. Thus, the spurious ringing, by conventional subwoofers' misbehaving response to every bass transient, actually causes distortion of all the rest of the program that is playing, making even midrange and treble information sound dirtier and more artificial, as well as more temporally smeared and hence less transparent and less fast (FM distortion temporally smears the sound by effectively jittering the signal's temporal reference).

And yes, this distortion is clearly audible. To give you a sneak preview of some discussion below, one of the biggest and most surprising sonic benefits of the TRW subwoofer is that it makes the whole system sound cleaner and clearer and faster and more articulate, even for midrange and treble information. This proves that this FM distortion of the room air and ear, by conventional subwoofers and woofers, is clearly audible, and that the TRW offsets and effectively erases this distortion (below we'll explain how).

It's another bitter irony that, even though an important benefit of subwoofers is the reduction of FM Doppler distortion from the woofer cone, by offloading some excursion from the woofer cone, conventional subwoofers then undo this benefit by re-introducing FM Doppler distortion in a different way, via their spurious ringing that modulates the air and your ear. And it's doubly ironic that employing vented enclosure designs for conventional subwoofers, in order to make their flat amplitude response extend lower in frequency, thereby makes this spurious ringing worse, and therefore causes worse FM distortion of the whole rest of the spectrum output by your system.

E.3.f. Erroneous System Waveform with Conventional Subwoofers

There's a further sonic problem caused by conventional subwoofers, with their errant time domain response. For your system as a whole to accurately reproduce the input signal waveform, all loudspeaker drivers should be contributing the correct kind of signal at the correct time. The ideal subwoofer, for each bass transient that comes along, should put out a signal that acts as an energy pedestal or foundation, for algebraically adding to the signal that is simultaneously put out by all the other loudspeaker drivers in your system, and this pedestal should remain at full and constant height (for the step signal input, acting here as an indicative test probe). This pedestal from the subwoofer is very important, because there is so much energy in the bass region, so the subwoofer effectively elevates the energy put out by the other drivers to the correct height, so that the signal from your loudspeaker array as a whole achieves the correct height and the correct waveform shape for accurate replication.

But we have seen that conventional subwoofers fail to put out the correct pedestal height, in all three regions of their misbehaving time domain response. In the first region, conventional subwoofers decline too quickly, instead of maintaining the correct signal height as a pedestal. In the second region, they actually go down to negative height, putting their supporting pedestal underground instead of high above the ground. And in the third region they oscillate spuriously between various heights above and below ground, for their supporting pedestal.

Thus, conventional subwoofers fail miserably to perform their time domain duty of providing a full height, correct pedestal for the signal waveform put out by all your other drivers. Conventional subwoofers put out the wrong signal levels at the wrong times, so when their acoustic output is algebraically added, instant by instant, as a supporting pedestal to the acoustic output from your main loudspeakers, the summed result is a royal mess, a very inaccurate signal waveform that is presented to your ear by the system as a whole. Without the correct pedestal, the waveform put out by your system as a whole is all wrong, especially because the bass region with its high energy constitutes so much of what should be the overall signal waveform's full and accurate content. By failing to put out the right waveform energy at the right time, conventional subwoofers fail to furnish the required high energy pedestal needed for your whole system to achieve correct waveform dynamics and accuracy. And then conventional subwoofers compound their felony by their spurious behavior later in time, their negative overshoot and ringing, which adds to your system the wrong spurious garbage sounds at the wrong time.

In short, conventional subwoofers, by providing a wildly and grossly inaccurate pedestal, doom your system to putting out a very inaccurate signal waveform. This creates many sonic degradations of your whole system's output (degradations beyond poor quality bass from the subwoofer itself), these system degradations including compromised dynamics, obscuration and distortion of the whole spectrum, and an overall system sound that simply sounds wrong and unnatural, like artificial hi-fi instead of real music, real voices, real sounds. Once you train your ear to hear this wrongness, you'll have a hard time accepting the sound of systems with conventional subwoofers ever again. Once you hear the TRW subwoofer in direct comparison, and hear how the TRW creates a correct pedestal and thereby makes the whole system sound right, you'll never want to go back to a conventional subwoofer, ever again.

E.3.g. TRW Time Domain Response

As promised, we've discussed the many, many sonic problems that conventional subwoofers create, due to the many ways in which they make a royal mess of time domain response. Now, what about the TRW subwoofer? How does its time domain response contrast with conventional subwoofers?

Simple. The TRW subwoofer's time domain response is essentially perfect. All those many gruesome errors in time domain response committed by conventional subwoofers: gone, since they never arise in the first place. All the many degrading sonic consequences discussed above, created by conventional subwoofers' time domain misbehaviors: gone, since they never arise in the first place. How's that for contrast?

How can the TRW subwoofer possibly have no problems whatsoever with time domain response in the bass, when all conventional subwoofers have so many problems that are so severe? How can it be so radically different, so radically opposite in its behavior and performance?

Simple again. The conventional subwoofer is inherently an AC device, so it gets into progressively worse trouble at very low frequencies, especially because it has high reactance at low bass frequencies. The TRW subwoofer is just the opposite. The TRW is inherently a DC device, so it is perfectly happy reaching down to ever lower bass frequencies, without limit, and without misbehaving, and the TRW does not have any reactance at very low frequencies.

In its time domain response to our standard test signal, the step, the TRW is essentially perfect. It reproduces the step accurately, and thus reproduces all bass, both bass transients and bass steady tones, accurately. The TRW's time domain response to the step test signal is the opposite of conventional subwoofers; the TRW does not start declining and wimping out too soon, and it does not have any negative overshoot, and it does not have any ringing. Obviously, then, all the many sonic problems discussed above, which conventional subwoofers cause by their too quick decline and negative overshoot and ringing, simply don't exist for the TRW.

The TRW simply reproduces essentially perfect quality bass. Conventional subwoofers, in complete contrast and opposition, make a royal mess of bass quality, and also even manage to mess up midrange and treble information in so doing. In contrast to conventional subwoofers, the TRW keeps pushing positive airflow and pressure, so long as the input signal instructs it to. This means that the TRW's bass quality gives you far superior impact and weight (since it does not decline too soon), and solid, tight definition (since it does not go negative), and dynamics (since it does not partially cancel its own previous output, nor the output from your main loudspeakers), and sonic waveform accuracy in itself (since it does not spuriously ring), and sonic waveform accuracy from your whole system (since its creates a correct pedestal for the waveform put out by your main loudspeakers).

Plus, the TRW gives you overall system sound throughout the whole spectrum that is far cleaner, clearer, faster, more articulate, more natural, and more accurate (since it does not distort nor time smear, via FM distortion, the wide spectral range acoustic signal put out by your main loudspeakers (indeed, we found that the TRW even acoustically reduces the FM distortion inherent in your main loudspeaker system, as will be discussed below).

E.3.h. Time Domain Response Summary

Audiophiles, accustomed to comparing conventional subwoofers with each other, naturally talk first and primarily about how low in bass frequency a subwoofer extends, and how loudly it can play bass. The TRW does extend far lower in frequency and play louder than all conventional subwoofers. And these are important factors, to be sure, in producing better quality bass and greater quantity of bass. But, as a wary audiophile might note, these differences are merely differences of degree, and make the TRW merely a bigger, better, badder subwoofer.

On the other hand, the differences in time domain performance we have just discussed above, between the TRW and conventional subwoofers, are emphatically not merely differences of degree. The TRW behaves in a wholly different way in its time domain response, and thereby produces a wholly different type of bass. And remember that time domain performance is more important, and more directly indicative of what we hear, than frequency response is, since signal change happens in real time, since subwoofer driver behavior happens in real time, since subwoofer output algebraically adds with main loudspeaker output in real time, and since we hear in real time (with our brain doing temporal integration and time-slicing analysis).

It is in the time domain performance that we can most clearly see that the TRW is a radically different type of subwoofer, which is fundamentally the opposite of conventional subwoofers, and which has strengths at low bass frequencies (indeed down to DC) where conventional subwoofers are riddled with severe weaknesses. Since it is the primary responsibility of subwoofers to capably handle exactly these same low bass frequencies, we can see that conventional subwoofers are miserable failures at their primary job, and therefore cannot even truly be called subwoofers. The TRW is the only subwoofer.

Part III: Relevance

We've been taught all our lives that human hearing extends only down to 20 Hz, and that the deepest bass musical instruments extend only down to 20 Hz (16 Hz for the rare 32 foot organ pipe). So how and why could a subwoofer that goes any lower than 20 Hz, like the TRW, even be relevant to human hearing, or relevant to program content?

A. The True Fundamental Concept of Frequency

The TRW is actually worth getting instead of a conventional subwoofer, just for its vast superiority in time domain response, which is so important and has so many sonic benefits, as just discussed above. But, for many audiophiles who are accustomed to thinking primarily in terms of bass frequency response and deep bass extension, there might be lingering doubts about the relevance of investing in a subwoofer like the TRW that goes below 20 Hz, and whose frequency response extends flat so far below 20 Hz, indeed down to DC. After all, we've been taught that there is no program content much below 20 Hz, and furthermore that humans can't hear below 20 Hz. So what's the point?

Moreover, the many, technically knowledgeable engineers, who design all our equipment, are extremely well versed in the concept of frequency, since the concept of frequency, and frequency response as a design tool, is their major stock in trade. They have largely been satisfied at designing and specifying our equipment down to just 20 Hz, especially transducers such as loudspeakers, which are very difficult to design for lower bass frequencies. So shouldn't we take a clue from these professional design engineers? Don't they know what they're talking about, and designing equipment for?

As a matter of actual fact, no. Nearly all design engineers in fact have a fundamentally erroneous view of frequency response, and don't even truly understand the basic concept of what frequency is and means. Since frequency is their key stock in trade, and frequency response is their key design tool, their erroneous understanding means that they have questionable right to even be designing our equipment in the first place.

You see, the popular but erroneous view of the concept of frequency and frequency response, shared by most design engineers, is based on a model of sine waves, sine waves at specific single frequencies. But the true definition of a sine wave at a single frequency is a single sine wave pattern that stays absolutely the same, unchanged, for a period of time that lasts forever. In the real physical world there is no such animal. Forever is a very long time.

Moreover, we would not want such an animal as our program material. A single sine wave that stays the same, unchanging forever, cannot contain or convey any information whatsoever. And we want our program material, be it music, voice, or film sound effects, to give us information. The only way that our program material can convey information is to keep changing, and indeed it conveys information only to the extent that it does keep changing, from one minute to the next, from one moment to the next.

B. Program Content: Change and Transients

The very definition of music involves a series of notes or sounds that change over time, as do the definitions of vocal singing, vocal speech, and sound effects. These changes totally invalidate the sine wave model of frequency, since that model is based upon and requires a single simple sound to stay the same, unchanged, forever.

Why? Because change logically implies that every musical note, every vocal sound, every sound effect sound, must have a temporal beginning and a temporal end (an end to make way for the next note or sound in the changing pattern, and obviously a beginning when this sound began to make the change from the previous, different sound).

This temporal beginning and end, indeed any temporal signal change that does not regularly repeat forever (as a single simple sine wave does), brings with it a wholly different conceptual view of what frequency is. This different conceptual view shows the true, correct conceptual way to look at frequency. And it is also the view that is correctly relevant to our actual program material, because our program material is continually changing.

Any and every sound that has a beginning and an end actually contains not a single frequency, nor even a few distinct frequencies, but rather in fact contains an infinite number of frequencies, and an infinitely dense spread of frequencies, and a spread that has a very, very wide spectral range. Any and every change in sound likewise actually contains a very wide spectral spread, of an infinite number of frequencies that are infinitely dense. And, because all our program material does convey information, all our program material in fact consists of a very wide spectral spread of frequencies, an infinite number of frequencies with infinite density along the frequency axis.

Thus, our program material is properly modeled as a series of transients, not as a sine wave or sum of sine waves. A transient, as its very name implies, is temporally present and with us only for a temporary period of time (as opposed to a sine wave's presence forever, by definition). A transient is a transient, who temporally passes through our presence, entering and then departing, as it starts and then later stops. This fundamental transient nature, of all our program material, is what makes and allows our program material to convey information (musical, vocal, or sound effect).

C. True Frequency Content of Transients

There is also a correct engineering way to model transients. A transient marks a change or transition in the signal. The simplest possible test signal, which can be used to model all transients with their changes or transitions, is a step test signal, which contains but one single, simple transition in the signal (an impulse is also usable, but it technically contains two transitions, up and then quickly down again, so we'll stick with the simpler step as a test signal model). So, let's now ask the key question: what is the true, actual frequency content of a step signal transition? And, of particular relevance to our subwoofer discussion here, how low in frequency does this frequency content extend?

The answer is simple. A step signal transition contains energy at all frequencies, spectrally extending an infinite number of octaves all the way down to zero Hz (DC)(an infinite number of octaves because each octave, each halving of frequency, takes you only half of the distance remaining to zero), and all the way up to infinity (or to the high frequency limit implied by the risetime of the signal source).

The implications of this finding are staggering.

This finding means that the whole model we have been taught of the sound from musical instruments, as consisting of a fundamental sine wave plus harmonic overtone sine waves at a few discrete frequencies, is, though crudely useful for some primitive purposes, fundamentally and wholly wrong for the sophisticated purpose of high fidelity reproduction. That's especially true for sharp signal changes or transitions, such as attack transients, which we of course want accurately reproduced by our equipment. Virtually all musical attack transients actually contain an infinite spread of frequencies, extending all the way down to DC and as high as the risetime of the attack warrants. Indeed, the only musical sounds that obey the common sine wave model are legato notes which begin slowly and gradually, without any attack at the beginning transition, for example many notes played by woodwinds or organ pipes.

C.1. Transients of Midrange and Treble Notes

This finding also means that most attack transients, even for musical notes whose sustained pitch is at some discrete frequency, actually contain an infinitely dense and very wide spread of frequencies. And this in turn means that they will excite and trigger any and all misbehaviors in all your system components, even though those misbehaviors might nominally be at specific frequencies far removed from the discrete frequency representing the sustained pitch of the musical note after the initial transition and transient attack.

For example, even though the sustained pitch of a musical note might be in the lower midrange, its transient attack at the beginning contains energy at an infinite spread of frequencies, so it will excite and trigger a misbehaving resonance in the upper midrange of your main loudspeaker's midrange driver, and this misbehaving upper midrange resonance will then continue to ring and artificially color the sustained portion of the musical note, artificially coloring it both by the foreign tonal energy in the upper midrange, and also by the foreign material sound of this ongoing resonance (say a papery mechanical coloration from the paper midrange cone breaking up). Or, the high frequency energy contained this attack transient could trigger tweeter misbehavior, even though the sustained later portion of the musical note lies in the lower midrange.

As another example, more to the point here, this attack transient, for a nominally lower midrange musical note, also contains energy at frequencies down to DC, so it would also trigger all the misbehaviors discussed above in conventional subwoofers. In other words, it is a fallacy to assume that the many misbehaviors discussed above for conventional subwoofers, and the many sonic degradations therefrom, occur only when deep bass musical notes come along. These conventional subwoofer misbehaviors are in fact triggered by virtually all attack transients. Indeed, these conventional subwoofer misbehaviors stick out more like a sore thumb, and are more obvious and obnoxious, when the musical note with the triggering attack transient is not nominally a bass note, but instead has its sustained pitch in the midrange or treble, and is therefore nominally a midrange or treble note. That's because the sustained portion of this midrange or treble note does not have much or any bass energy that might usefully mask or hide the ongoing, ringing misbehavior of a conventional subwoofer.

This finding also means that transient attacks actually require far more extended treble capability by your system, to be reproduced correctly, than the traditional musical model, of musical instruments emitting only sine wave fundamentals plus overtones, would suggest is adequate. For example, we measured the frequency content of a gentle cymbal kiss (such as just before the final coda in Rachmaninov's Second Piano Concerto), focusing in on the attack transient that starts this gentle, quiet cymbal kiss. Its actual frequency spectral content was, as predicted, a very wide, infinitely dense spread of frequencies. The shape of the energy content, as a function of frequency, was a broad hump, with skirts extending far above and far below the center frequency of the main peak of this hump. And, what was most interesting, for the point of our discussion here, was the frequency at which this center peak of the hump was located. This frequency could in a sense be called the fundamental frequency of this gentle cymbal kiss, since the maximum energy was at this frequency. What was the fundamental frequency of this gentle, quiet musical transient? It was 40,000 hz!! And the spectral content showed large amounts of energy extending far beyond 100,000 Hz, the limit of our measuring microphone and FFT analyzer.

Incidentally, as a technical aside, if a musical transient is identically repeated many times, and at identical temporal intervals, then its characteristics fall between a single transient and a sine wave that identically repeats, so its actual spectral content does not range as wide in frequency as does the actual spectral content of a single transient, nor is its spectral content infinitely dense. But in practice, even repeated musical transients are not performed identically, and not at identical intervals, so they become individually different transients, similar to truly singular transients that are never repeated. Thus, for practical purposes, we can regard virtually all music as consisting of singular transients, actually containing infinitely dense spectral energy, and containing a very wide frequency spread of energy, down to (but not including) DC.

We've just discussed the staggering implications of our finding for musical notes that are nominally midrange and treble musical notes. Similar implications naturally also apply to all vocal sounds, dialogue, and sound effects, which of course are richly laden with attack transients.

C.2. Bass Content of Transients

Now, what about notes that are nominally bass notes? Well, which musical instruments actually produce the deepest, lowest frequency bass?

Let's take a moment for a pop quiz. Consider the mighty pipe organ, often cited as the musical instrument with bass reach to the lowest frequency of interest for high fidelity reproduction. And let's pit this pipe organ against the most absurd possible competition, musical instruments that are nominally considered to be the highest frequency instruments in the orchestra, such as the violin or triangle.

Take a guess as to which real musical sound has the deepest bass, and therefore requires the deepest bass frequency extension from a subwoofer to be correctly reproduced by your system, the biggest pipe of a pipe organ, or the attack transient of a triangle ting - or, even more absurdly, a pluck on the highest frequency violin string, stopped down to its shortest length to yield the highest frequency (this is a real musical sound, such as you'll find a little over a minute into the fourth movement of Bartok's Fourth String Quartet).

The pipe organ's biggest pipe (found on only a few organs) plays at 16 Hz, and, because an organ note starts slowly, it does not have any significant attack transient, so its frequency content does not extend below 16 Hz. In contrast, the attack transient from the highest frequency violin string, stopped down to its highest frequency, actually contains energy all the way down to zero Hz (DC)!!

This shocking result is predicted by the fundamental theory of frequency (for those who truly understand the concept of frequency). And we verified this result by actually measuring the frequency content of a real violin pluck, wherein the FFT analyzer showed energy all the way down to (but not including) DC.

C.2.i. Mathematical Corroboration

We then further corroborated this result by asking our friend Glenn Rankin to do a mathematical analysis. Glenn used as a model a single cycle of a sine wave, which, like the FFT analyzer showed, would not have any energy content at DC itself, and which would be a decent model for a string being plucked in one direction, then spontaneously going back in the other direction, and then quickly being damped to zero. So, what do you think is the actual frequency content of a sine wave, but only a single complete cycle thereof? In particular, how low in frequency does the energy content of this signal actually extend? Well, you might say, that depends on the frequency (or periodicity) of this sine wave cycle.

No, it doesn't. And this serves as a good illustration of the fundamental misunderstanding of sine waves and music that we have all been taught, and that most design engineers still mistakenly believe. You see, this signal is not a sine wave. For it to be a sine wave, it would have to continue cycling, unchanged, forever, with no beginning and no end. But this signal does change, just like all our program material does. This signal first is nothing, then starts, then has a waveform shape that deceptively is the same as a single sine wave cycle, and then stops. So this signal, rather than being a sine wave, is instead a transient, which appears and then disappears over time. The start and stop of this single sine wave cycle might be relatively gradual, rather than a sudden, steep attack, but it is still a transient. Note also that this means that even clarinet and pipe organ notes, which begin and end gradually, and which also have a simple sine wave shape while they are playing, are nevertheless still transients, because they too are temporary, and therefore they too actually contain a spectral frequency spread that extends beyond the single frequency represented by their pitch.

What then about the actual frequency content of this single sine wave cycle? Glenn Rankin's mathematical analysis, transforming this time domain signal into the frequency domain, showed that its actual spectral frequency content extends all the way down to DC. It does not happen to include DC, because this model signal is symmetrical about the zero axis. But this signal still requires a subwoofer that extends all the way down to (but in this case not including) zero Hz, in order to be reproduced accurately by your system. And this is true regardless of the nominal frequency or periodicity of the sine wave, whose single cycle we excerpted to make this model signal.

Incidentally, the full spectral frequency spread, of energy contained in this single cycle of a sine wave, has a broad hump shape, with energy spectrally extending far above, as well as far below (down to DC) the frequency of the hump's peak. And the frequency of the hump's peak is at the frequency or periodicity represented by the frequency of the sine wave whose single cycle we have excerpted. Thus, it makes good sense to speak of this peak, of the broad hump's spectral energy distribution, as representing the fundamental frequency of the transient (just as we did above for the cymbal kiss, whose spectral energy distribution hump was centered about, and peaked at, 40,000 Hz).

D. Summary of Actual Program Content at Bass Frequencies

We have now demonstrated that musical transients, even ones at nominally high frequency, actually have spectral energy content down to DC, and therefore require a subwoofer that can play accurately down to DC, if your system is to reproduce these musical transients accurately. We demonstrated this by analyzing the true fundamental concept of frequency, and by actual measurement, and by mathematical analysis. The only remaining step, to prove the pudding and close the case, is to corroborate this by listening comparisons, which we will discuss below.

Since musical transients, including nominally high frequency ones, actually contain spectral energy down to DC, then obviously so also do all vocal utterances, which a laden with starting and stopping transients, and nominally occur in the midrange. And film sound effects obviously can contain very low frequency energy, including sound effect transients that nominally have a very high frequency.

Today's recording chains can have very good, very extended response to very low bass frequencies. In fact, with today's solid state circuitry and digital recording, both of which can be perfect down to DC, the only filter acting to reduce very low frequency spectral energy is the recording microphone capturing the original sound. Microphones can extend very low in frequency (especially omnidirectional ones), and a microphone's low frequency rolloff slope is not that steep, so microphones can still put a reasonable amount of spectral energy onto a recording of a live sound, say down to .1 Hz or so. Thus, it clearly becomes important to have a subwoofer that extends accurately down to say .1 Hz, in order to correctly reproduce live sounds as they actually exist on our program material.

Then, consider that many film sound effects never pass through a microphone at all, but instead are synthesized electronically and put directly onto the soundtrack. Thus, many film soundtracks contain abundant energy at extremely low frequencies. For example, the massive thuds of a dinosaur's foot might be synthesized by gating a sine wave oscillator set at say 3 to 5 Hz, so proper reproduction of this sound effect requires a subwoofer that is comfortable putting out huge amounts of bass energy at 3 to 5 Hz, plus a heck of a lot lower in frequency, in order to accurately reproduce the transient start and stop of each footfall (as we just saw above, a gated signal comprising a burst of a single or a few cycles of sine wave actually contains spectral energy all the way down to DC).

E. Human Limits for Low Bass Perception

Let's turn now to the low frequency limits of human perception. Scientists tell us that humans cannot hear below below 20 Hz, which implies that there is no need for subwoofers to extend below 20 Hz, regardless of what we found above about program material actually extending far below 20 Hz.

But again, what scientists have taught us is woefully fallacious. And again, the reason for their mistaken belief is that they don't understand the fundamental concept of frequency, and erroneously rely upon a sine wave model.

E.1. Sine Waves vs. Transients; Frequency vs. Time Domain

Scientists test this human hearing limit only with continuous, unchanging sine wave tones. The standard test simply plays a sequence of sine wave tones, at ever lower frequencies, until the human subject reports that he can no longer hear the sine wave tone.

But this test is doubly irrelevant. It is firstly irrelevant because it does not represent the type of bass that is to be heard from our program material. As discussed above, the vast majority of low bass from our program material consists of bass transients, not steady bass tones (the only exceptions being the pipe organ and the contrabassoon). It is secondly irrelevant because the human mechanism for perceiving transient bass events, in the actual time domain in which they really occur, might well be very different from the human hearing mechanism they are testing, which involves hearing continuous tones in the frequency domain.

These scientists fail to comprehend that real program material is composed of changing transients, not unchanging tones, and they fail to see that the human mechanism for perceiving and evaluating changing transients in the time domain might well be totally different from our mechanism for hearing unchanging sine wave tones in the frequency domain.

What, then, would be a more relevant, more meaningful way to test human low frequency perception capability? Let's take a lesson from above, where we found that it was more revealing and relevant to evaluate subwoofer performance in the time domain, rather than the frequency domain, and where we found that a transient test signal was a more revealing and relevant probe of subwoofer performance than a sine wave was. So, let's evaluate human performance via the same principles we found so helpful in evaluating subwoofer performance. Let's test human performance with a transient test signal, a signal that probes and exercises human perception capabilities in the time domain.

This plan also fits in perfectly with the real task that we are testing humans for. Since program material contains far more occurrences of low bass information arising from transients rather than from steady tones, it's obviously far more relevant to test human low frequency perception ability using transient signals rather than steady sine wave tones. And, in case humans do employ a different detection or analysis mechanism for transients than they employ for steady tones, perhaps a mechanism that operates in the time domain rather than the frequency domain, our use of a transient test signal would correctly and relevantly engage this human mechanism -- whereas the scientists' use of steady sine wave tones would utterly fail to engage this human mechanism, thus totally failing to reveal the true low frequency perception abilities of humans, especially for precisely the type of bass information (transient rather than steady tone) that humans will be receiving most from their program material.

E.2. Experiment to Test Human Bass Sensing Limit

As we saw above, the simplest possible transient test signal is a step signal, which has merely one transition or change. The step signal as a test contains all frequencies, so in one instant it presents a human subject with all frequencies he could possibly perceive. The basic idea of the experiment is to play a step signal repeatedly for the human subject, while the lowest frequencies of the step signal are being electrically filtered at various low frequency points, in order to discover where the human can detect a qualitative difference in the sound of the step, as the low frequency rolloff point is changed, and where he cannot.

This experiment could be designed in various specific ways, and we'll just describe one protocol as an example. First, play the step signal (from a signal generator) through a bass (high pass) filter that filters out frequencies below say 40 Hz, and play this step repeatedly, so the human subject gets acquainted with its sonic qualities. Then, change the filter to filter out frequencies only below 20 Hz, and play it repeatedly, asking the human subject if he can hear any difference. If you wish, you can double check the validity of the human subject's responses by various methods, for example by wiring a switch so that, when you tell the human subject that you are (or he is) switching to half the frequency for the filter, in reality the filter is staying at the same frequency.

Continue this progression, cutting the filter frequency in half, so long as the human subject can reliably detect a difference in the sonic qualities of the step test signal transient. As this progression goes lower in filter frequency, you will reach a point where the human subject can no longer detect a difference in the sonic qualities of the step transient, when you cut the filter frequency in half. This point is the key frequency.

This point tells us that the low frequency bass limit of human perception extends at least this low, in perceiving bass quality of real program material transients (as accurately simulated here by our step test signal transient), most of which actually have spectral energy down to DC. This point tells us that subwoofers must extend at least this low in bass frequency reproduction, in order to fully satisfy human bass perception capability, on real program material transients. This point tells us that, if a subwoofer extends at least this low, then its output should be sonically indistinguishable (to humans) from a subwoofer that extends even lower, so it should be good enough.

We performed this experiment years ago, and the results seemed shocking at first. We found that, when listening to this highly relevant bass transient test signal (instead of the irrelevant conventional sine wave test signal), we could perceive a difference in bass quality all the way down to about .1 Hz (!!!). And that was using conventional loudspeakers to perform this test, which partially masked the true measure of human bass perception capability, since they interposed an additional steep filter at about 40 Hz. When we get a chance to repeat this same test using the TRW subwoofer, whose response is essentially flat to DC, we might well find that human bass perception ability on transients actually extends even below .1 Hz.

But, for purposes of our review and discussion here, it's fine to use .1 Hz as a working approximation for the lower limit of human bass perception. No conventional subwoofer gets even close to this frequency, and the TRW extends down to .1 Hz and below with ease, so for purposes of our discussion here it doesn't matter whether the true human limit is .1 Hz or .01 Hz. In either case, only the TRW covers the entire bass range of human perception with ease, whereas conventional subwoofers don't even come close.

Most importantly, this experiment proves that humans can indeed easily perceive the sonic benefits of a subwoofer that extends far below the commonly accepted human hearing bass limit of 20 Hz. This proves that the TRW's ability to cover this spectral region, from .1 Hz to 20 Hz, and to do so accurately and effortlessly, is highly relevant to human perception abilities in this spectral region, and it places the TRW at a crucial advantage over all conventional subwoofers, which cannot cover this relevant spectral region at all.

E.3. New Major Role for Subwoofer like TRW

This finding also causes us to rethink the whole role of a subwoofer in your system, and its importance to your system. Old fashioned thinking, based on conventional subwoofer technology and capability, has a subwoofer adding merely one octave, 20-40 Hz, to a high quality loudspeaker array employing full range systems that capably cover 9 octaves, 40-20,000 Hz (satellite system abominations are not worthy of serious inclusion here). Thus, with the limitations of conventional subwoofers, the subwoofer has a relatively minor spectral span to cover, and a relatively minor supporting role to play.

But this picture completely changes with a true subwoofer like the TRW, which can finally cover the full human spectral perception capability at low frequencies. There might be 9 octaves for your full range loudspeakers to cover, as they cover virtually all of what used be thought of as human hearing spectral range and virtually all of what used to be thought of as program material spectral range. But we have now discovered that both program material and human perception extend at least down to .1 Hz. And the spectral range from 40 Hz down to just below .1 Hz also happens to span 9 octaves. This means that the job of a competent subwoofer is fully as important as the full range loudspeaker's job, since the spectral range it must cover accurately is just as wide.

This also explains some of our sonic findings discussed below, where we found that the sonic benefits from the TRW subwoofer not only were dramatic where we expected them to be, in better quality and quantity of bass, but also were surprisingly far reaching, dramatically improving other aspects of system sound that we had never suspected could or would be improved by a subwoofer. These further improvements, in unexpected sonic aspects of overall system sound, make good sense in light of this new fact, that fully half of the spectral range from the whole system is actually contributed by a competent subwoofer, such as the TRW.

E.4. Conceptual Analysis of Human Bass Sensing Ability

The fact that human bass perception actually extends down below .1 Hz might seem shocking, to those who have been schooled to think only in sine wave and frequency domain terms. But this fact makes good sense if we think about this in the time domain instead of the frequency domain, and use relevant transients instead of irrelevant sine waves as our model.

To understand this intuitively, picture first the vision of a hummingbird. As you know, hummingbirds live their lives at a very fast pace, and have a very short attention span. Thus, if you stand near a hummingbird and move about, the hummingbird can't see your actual motion, and thinks you are standing still. Similarly, we humans have a visual attention span that is longer than a hummingbird's, but still limited. Our visual motion detection threshold is just a bit faster than the sun moves across our sky, so the sun looks to us as though it were stationary in the sky, even though it is in fact continually moving slowly (we can indirectly infer this unsensed motion only when the sun is setting at the horizon, and keeps altering its position relative to the horizon).

A similar phenomenon occurs with human perception of acoustic energy. We can sense the amplitude change or decline, i.e. amplitude "motion", only when it occurs reasonably rapidly.

E.4.i. Change That's Too Slow to Detect

Suppose for example that we play our step test signal, unfiltered, through the TRW subwoofer that can reproduce bass frequencies down to and including DC. The full amplitude of the step, after its transition up from zero amplitude, would last forever. But, could we tell via our perceptions that its full amplitude is staying the same forever? Of course not, since we won't be alive when forever arrives.

Suppose next that we play the same step test signal through a very, very low frequency electrical bass filter, a filter which would make the step signal decline at a slow rate, so that the signal amplitude fell to a significantly lower level after say 2 minutes. That 2 minutes is surely well beyond our human attention span, so we could not detect the actual slow movement of the signal amplitude's downward sloping decline. In effect, the rate of change is too slow for our attention span capability to detect it.

Then, suppose next that we set the electrical filter one octave higher, which would mean that the step signal's amplitude would decline (move downward) twice as fast, declining to a given lower amplitude level in half the time, 1 minute instead of 2 minutes.

Now comes the key question: could we tell the difference in sonic quality, between the very, very slow motion of the decline that takes 2 minutes, vs. the very slow motion of the decline that takes 1 minute? Probably not, because even the 1 minute decline has a downward slope that is too shallow, a downward motional speed that is too slow, for us to detect. Our attention span is simply not long enough to sense this downward acoustic energy as a motional change in energy over time, in much the same way that our visual attention span is not long enough to see the actual, real motion of the sun in mid-sky.

The only way that we could tell any difference between the bass filter set at 2 minutes vs. the bass filter set at 1 minute would be via an indirect inferential method, such as noting a time difference on the clock when the differing step signals finally seemed to fall silent (analogous to our indirectly, inferentially "seeing" the motion of the setting sun at the horizon, by noting the progressively smaller dimensions of its shape). Thus, it seems clear that human bass sensing ability does not require a subwoofer to extend so low in bass that it takes 2 minutes to decline instead of 1 minute (a one octave higher bass cutoff), for an input signal transient (be that transient a singular signal transition from program material, or a singular signal transition from a step test signal).

E.4.ii. Change That's Fast Enough to Detect

So let's next change the time frame of this thought experiment. Let's set the electrical filter so that the step signal declines most of its amplitude within 2 seconds, not 2 minutes. This puts the filter's rolloff corner at a 60 times higher frequency. We can all agree that the human brain is capable of paying attention to the sonic quality of a big, whopping bass thump for the very short time of a mere 2 seconds. Moreover, humans can surely directly sense the difference in sonic quality when a bass thump lasts for only 1 second instead of 2 seconds. In effect, the step signal's amplitude decline is now fast enough so that we can now sense the actual difference in the sonic quality between a slower 2 second decline and a faster 1 second decline.

When the electrical filter was set for a 1 minute or 2 minute decline, the acoustic amplitude in the room was actually changing all the time, but we could not directly sense this change as making any difference in the sonic quality of the bass thump. Moreover, we could therefore also not directly sense any difference between the 1 minute vs. 2 minute decline, so it was not important to our human sensing which of these very low frequencies this filter was set at. Analogously, even though the sun is actually moving across the sky, we cannot directly sense its motion, so it appears to be motionless, and, moreover, we could not directly sense any difference in the sun's actual motion if in fact it were to move twice as slowly across the sky.

But now, with the electrical filter set for a 2 second decline, which is well within our human attention span, we can indeed directly sense the actual change over time in the acoustic bass signal. And, moreover, we can therefore also sense the difference in rate of decline, and the difference in sonic quality of the bass thump, if the electrical filter is set for a 1 second decline instead of a 2 second decline. To continue our analogy, if a propeller airplane moves across the sky, it is moving a lot faster than the sun, so we humans can indeed directly see its motion. Moreover, if a jet airplane then flies across the sky at twice the speed of the propeller airplane, we can easily directly sense the difference in the quality of speed between the two airplanes.

The fact that we can and do sense a difference in sonic quality, between the bass thump having a 1 second decline vs. the bass thump having a 2 second decline, means that it becomes sonically important to set the filter at the lower frequency (the longer 2 decline), if we want our system to reproduce the full bass spectrum that humans can sense, and if we want the quality of the bass thumps to have the maximum high quality that humans can sense and benefit from.

For argument's sake, let's now suppose that it turns out that we humans cannot directly sense any sonic difference between the bass thump that declines in 2 seconds vs. a bass thump that declines in 4 seconds (achieved by setting the electrical filter one octave lower in frequency than for the 2 second decline). This means that, so far as human bass sensing capability is concerned, it is not important to have a subwoofer extend so low in frequency that it can output a 4 second decline from an input step test signal. It is sufficient, for the intended human audience, to have the subwoofer extend only low enough in frequency to output a 2 second decline.

Incidentally, note that we do not need to postulate here that the human brain can indeed pay attention to a bass transient for the full 2 seconds. That's because the 2 seconds represents the total time that it takes for a filtered step to decline most of the way toward zero. And this 2 seconds for the total measured decline implies a fairly rapid rate of declining change within that 2 second time period, instant by instant.

What the human brain might well be focusing on, with its time domain perception and analysis capability, is this fairly rapid rate of declining change implied by the 2 second total time period, even if the brain has an attention span of say only a fraction of a second, and thus only looks at this rate of change for this fraction of a second. What counts here is that the rate of change is fast enough, when 2 seconds is the total measured decline time, for the brain to detect downward motion, perhaps instant by instant, in the declining amplitude of the filtered step.

Meanwhile, when 4 seconds is the total measured decline time, the rate of decline is slower, so, in our posited case here, the brain cannot sense downward amplitude motion of the signal.

Analogously, the human eye and brain can tell that an airplane is moving across the sky, with just a glance that lasts only a fraction of a second, because the rate of motion is fast enough, but the human eye and brain cannot directly see the sun actually move across the sky, even if it pays attention for a much longer time.

E.4.iii. Calculation of Low Frequency Limit

So let's run with a 2 second decline as a reasonable model. What bass frequency does this correspond to? In other words, how low in frequency does a subwoofer's response have to extend, in order to adequately cover a human's ability to pay attention for a mere 2 seconds, to the sonic qualities of a bass thump transient?

A simple engineering formula is used to convert this 2 second decline, called a time constant, into the equivalent frequency. That formula is F=1/2T, where T is the time constant (2 seconds) and F is the equivalent frequency (in cycles per second, ie. Hz). Plugging our 2 second time constant into this formula shows that the equivalent frequency is (trumpets, please) .08 Hz!!

This calculation means humans can directly sense bass quality down to .08 Hz, on all the real transients in our program material, transients which overwhelmingly outnumber steady (sine-wave-like) bass tones in our program material. This means that a subwoofer must be capable of extended, substantially flat bass response down to .08 Hz, if it is to adequately satisfy human bass sensing capability, in reproducing high quality transient bass sound (and, if the subwoofer does happen to have some rolloff at some very, very low bass frequency, then that rolloff point must be far below .08 Hz, in order that .08 Hz and above can be accurately reproduced in the time domain, so as to avoid incurring all the time domain problems discussed above for conventional subwoofers).

This calculation of .08 Hz, which equals .1 Hz when rounded to one decimal place, was based on a conceptual analysis of transients in the time domain. Thus, our previous experimental finding, that we could actually perceive bass quality on transients down to at least .1 Hz, is not as shocking as it might have seemed at first. Indeed, the two approaches agree perfectly with each other. The conceptual analysis and the empirical experiment corroborate each other.

By going to transients instead of sine waves, and the time domain instead of the frequency domain, we have gained a far more relevant and realistic picture, of what frequencies are actually contained in our program material, and of what frequencies humans can actually perceive. And it's a far different picture than the old-fashioned picture that embraces merely 20 to 20,000 Hz, which we can now see to be dreadfully wrong. It was wrong because it failed to understand the fundamental concept of frequency, and therefore used only a sine wave model, viewed only in the frequency domain.

E.5. Sensing Bass via Other Means

It's worth noting that humans can sense low frequency information by means and mechanisms other than by listening with the ears to sine waves. We have just shown, by conceptual analysis corroborated by empirical experiment, that the human brain must also be able to perform some kind of time domain analysis upon transients, in order to perceive the sonic effects upon bass quality, of filtering at extremely low frequencies (.1 Hz), when applied to transients of the kind that fill our program material.

Additionally, humans can obviously also sense high energy low bass by our sense of feeling. We all know that feeling of a kick in the stomach that a truly impactive bass transient can have and should have.

And we also feel bass with our feet, perhaps subliminally. Transients with a lot of bass energy also shake a room's structure, in particular the floor, where our feet are planted. Indeed, when there is strong bass transient we actually feel it with our feet before we hear it with our ears, because the shock wave travels faster through solid materials like the floor than it does through air.

In fact, a good portion of the thrill of truly impactive bass is the fact that our brain gets momentarily terrorized, in a primal caveman way, by the shock wave felt through our feet, before we can hear the explanation of this acoustic event arriving at our ears via the air, so for a split second our brain knows something is horribly wrong (e.g. an earthquake) and something big is coming, but it doesn't yet know what that something is.

F. Summary of Relevance

We have now seen that the extreme low frequency capability of the TRW is assuredly relevant, and indeed doubly relevant. It is relevant and crucial for accurately reproducing virtually all live transients recorded onto our program material, all of which actually have frequency content extending all the way down to DC -- not to mention the extreme low bass from synthesized sound effects that are directly electronically recorded onto film soundtracks, without any intervening microphone. And it is relevant to humans' ability to sense extremely low bass frequencies in all these transient acoustic events, down at least to .1 Hz. Thus, it is crucial for any subwoofer worthy of the name to be able to play, and play accurately, and play at full volume levels, all the way down at least to .1 Hz. No conventional subwoofer comes even close to this, so they are in fact not true subwoofers at all. The TRW does meet this subwoofer requirement, fully and effortlessly. So, once again, the TRW is the only subwoofer.

Part IV: The Sound of the TRW

We tested the sonics of the TRW in two distinct setups, first as a low frequency supplement to a system that already had a full array of conventional subwoofers, and second as the sole subwoofer mated only to main loudspeakers extending down to 40 Hz. We'll describe all our findings for the first setup first, and then later our findings for the second setup.

The pre-existing conventional subwoofers in the first setup were very capable, indeed spectacular, as conventional subwoofers go, representing the best that the state of the conventional subwoofer art can achieve. There were actually three conventional subwoofer systems, with huge driving cone area among them, and the largest conventional subwoofer being a monster in a huge enclosure that extends down to 16 Hz. The test protocol was simple. Play the system, including all these monster conventional subwoofers, without the TRW, then add in the TRW as a supplement, and note the sonic differences. We of course played a wide variety of program material, ranging from extreme low frequency effects on film soundtracks, to various kinds of music, including the high frequency violin plucks from Bartok's Fourth String Quartet, discussed above as an example of high frequency musical transients.

A. Film Soundtracks

Let's start with the most obvious, and most expected, sonic differences, and then move toward the more unexpected sonic differences (which actually turned out be even more dramatic and important). The TRW's manufacturer had prepared a burned DVD with excerpts from many films, containing a wide variety of low frequency sounds and sound effects.

Some of these sound effects were in effect very low frequency tones or rumbles, well below 20 Hz, which lent a palpable atmosphere to the room or space where the film action was taking place. Because they were well below 20 Hz, as proven by a live real time spectrum analyzer that was monitoring all proceedings, these sound effects were virtually or totally inaudible via the full system with the giant conventional subwoofers, but they were clearly audible and clearly felt physically when the TRW was added into the system. Very impressive, and just what one would expect.

Some of these sound effects were in effect gated bursts of sine waves, like the dinosaur footfalls in the Jurassic Park series. Here too, the deeper frequency reach and greater power capability of the TRW shone forth clearly. These sounds were impressive by normal hi-fi expectations from the conventional subwoofers alone, but, when the TRW was added into the system, the efforts of the world's best conventional subwoofers suddenly became wimpy and unimpressive in comparison.

With the TRW in the system, these sounds induced a feeling of primal fright in our gut, whereas with the huge conventional subwoofers these same sounds were just entertaining noise. With the TRW, you don't just hear sound effects, you also feel them (far beyond what even the best conventional subwoofers can do), so they become much more involving, more exciting, more terrifying, more dramatic. The physical feeling imparted by the TRW is so accurate to the sound effect being represented that the effect becomes very believable, so it physically brings you into the scene visually portrayed on the display (far more convincingly than those shaking theater chairs do).

A.1. Bass Transients from Soundtracks

We've saved the best, of film sonics, for last. The TRW is superbly impressive, and far superior to conventional subwoofers, when reproducing sound effects that, like the above, involve sine waves or gated pulses of sine waves, with bass energy around 3 to 5 Hz. But, when it reproduces bass transients, which reach all the way down to DC, the TRW is not merely superior or impressive, but instead gives you a wholly different type of experience, totally unlike anything you have experienced before on this planet.

It is bass transients which most strikingly reveal the fact that the TRW is a wholly different kind of subwoofer, not merely a bigger, better, badder subwoofer. You see, the sound effects above, based on sine waves with energy primarily only in say the 3 to 5 Hz region, result in strong output from the TRW but essentially no output from conventional subwoofers, so from these one might conclude that the TRW goes lower and louder in bass (which of course it does do), but does nothing else special (which would be untrue).

However, bass transients dramatically bring out the very best and most unique behavior from the TRW, since they show off the TRW's unique sonic abilities all the way down to DC (an infinite number of octaves below 3 Hz), plus they show off TRW's unique time domain accuracy. In contrast, bass transients bring out and highlight the weakest and worst behavior from conventional subwoofers, because, unlike the 3 to 5 Hz sine wave sound effects above, transients do get the conventional subwoofer to respond, and (as discussed above) conventional subwoofers respond with all kinds of phony sounding spurious sonic garbage, including overshoot and ringing and boomy overhang, even while they totally fail to convey the true solid impact that a bass transient should have.

Thus, bass transients highlight the very best (and most unique) sonic assets of the TRW, while highlighting the very weakest and most garbagy behavior of conventional subwoofers. And therefore bass transients most clearly demonstrate that the TRW is wholly different in its fundamental nature from all conventional subwoofers.

There are many different kinds of bass transients on film soundtracks, from slamming doors to shotgun blasts. And we could spend hundreds of words, telling you about the wholly different sonic experience the TRW gives you, as directly compared to the world's best conventional subwoofers, from these many kinds of bass transients. But instead, we can sum up all of this in three simple words.

Master and Commander.

The cannon shots in this film are very potent, and very realistic (we have a handy sonic reference standard in the live mortar fire we hear at a nearby military base). A cannon shot emits tremendous positive pushing airflow, which just keeps pushing, for a rather long time. From this, you hear and feel a tremendous thud, which hits your whole body and presses in upon it. Then, unlike the quick kick in the stomach from other kinds of transients, the positive pushing airflow pressure from the cannon shot just keeps on pushing at you, keeping your stomach compressed inward. This is probably the closest acoustic analog to the step test electrical signal we used above, to probe the very limits of bass performance, since the step also suddenly rises to a higher airflow level and then just keeps on pushing, for a long time. The bass from a real cannon shot is also surprisingly tight and dry, not boomy or woolly.

The TRW's reproduction of these cannon shots is thrilling, and superbly realistic. Since the TRW can inherently output huge amounts of airflow, and can effortlessly do so forever, with its response down to DC, it is intrinsically perfectly suited for accurately reproducing these cannon shots, just as it is for accurately reproducing the similar step test signal, which is the standard for examining a woofer's true capabilities at their limit.

Through the TRW, these cannon shots have such huge, huge, huge volume impact that your whole body will be limp with disbelief, that any loudspeaker of any kind, indeed anything short of a live cannon, could achieve this. And, through the TRW, the pushing pressure from each cannon shot continues in time, just as from a live cannon, rather than prematurely falling limp as it would from every other transducer that did not have full response down to DC. And, through the TRW, each cannon shot sounds tight, dry, and well defined, just like the real thing, since the TRW has essentially perfect transient response.

In contrast, the cannon shots through conventional subwoofers, even some of the best in the world, was a whole different story, when heard without the TRW. The initial impact was like being weakly patted with a powder puff. What little positive pressure there was, quickly died away, as these conventional subwoofers wimped out on the sustaining of pressure and went into premature decline (region 1) in the time domain, which is correlated to their premature bass rolloff in the frequency domain, at the relatively high frequency of 16 Hz (which is an infinitely higher frequency than zero Hz or DC). Their bass quality on these cannon shots sounded woolly, loose, boomy, and poorly defined, in complete opposition to the TRW, because the conventional subwoofers were doing their negative overshoot (region 2) and AC ringing (region 3) spurious misbehavior, rather than accurately tracking the input signal.

A.1. i. Spurious Garbage from Conventional Subwoofers

And we've saved the worst sonic offense for last. Just after their initial powder puff impact on the cannon shot, the conventional subwoofers went into sustained wild oscillating ringing, frantically flapping and pumping back and forth, in totally spurious misbehavior that was not at all representative of anything in the input signal, of anything in the actual sound of the cannon shot. This totally spurious mad pumping misbehavior sounded just like what it was, spurious garbage totally unrelated to the true sound of a cannon shot (it sounded even worse than a boomy bass overhang, which at least is related to the original bass sound).

What's going wrong here, so dreadfully wrong? As discussed above, conventional subwoofers spuriously ring, in their own cycling pattern unrelated to the input signal commands, in region 3 of their time domain response to a transient, and this ringing is especially bad, in both amplitude and sustained temporal duration, with vented bass subwoofers.

In this example of the cannon shot, this sustained spurious ringing was even worse than usual (on other kinds of bass transients), and was especially obnoxious sonically. That's probably because the input signal from the cannon shot is a transient with sustained energy, and massive amounts of sustained energy, and energy that is very near DC in frequency (as the cannon shot keeps up its positive push for a sustained duration). Thus, the cannon shot input signal keeps pouring massive energy into the conventional subwoofer at a frequency near DC. But the conventional subwoofer is inherently an AC device, and does not know how to accurately play this incoming energy that's near DC. But this massive incoming energy, near DC, keeps on coming for a sustained time, from the cannon shot. So, what can the subwoofer do with all this massive, sustained incoming energy near DC? It has to do something with all this incoming energy.

So the conventional subwoofer does the only thing it can, the only thing it knows how to do with incoming energy that's lower in frequency than the subwoofer system's resonance frequency. The conventional subwoofer dissipates this massive incoming energy by madly ringing at its resonance frequency, the pattern of this ringing being dictated by the conventional subwoofer's physical parameters, and not at all by the input signal, so that the ringing signal output is totally spurious garbage, which is totally unrelated to the commands of the input signal.

In effect, the conventional subwoofer takes in all the incoming energy below its resonance frequency (which it can't reproduce at the correct frequency), and converts this lower frequency energy into ringing energy at the higher frequency of its system resonance. And, because the lower frequency, near DC, energy from the cannon shot just keeps on coming temporally, the conventional subwoofer can do nothing but keep on ringing temporally, frantically flapping in a totally spurious way, and madly pumping as hard as it can, trying to dissipate all this incoming energy, and thereby creating the maximum amount of spurious garbage that it can, for a sustained period of time.

The conventional subwoofers are alternately pushing air into the room and sucking air out of the room, over and over, for a long period of time, whereas the true input signal from the cannon shot should be continually pushing, into the room air and into your body and ears, for this entire time. No wonder the conventional subwoofers sounded so obnoxious, and so phony, on these cannon shots!

And remember, this misbehaving conventional subwoofer just happens to be one of the biggest, best, baddest, most expensive subwoofers extant (even more expensive than the TRW), a subwoofer that has been widely praised as the best in the world heretofore. This conventional subwoofer is indeed a praiseworthy, excellent design effort, as conventional subwoofers go. But it is still a conventional subwoofer, so it is still inherently trapped by all the physical handicaps and roadblocks discussed above. Thus, it is clear that even the very best design efforts, in conventional subwoofer technology, pale (and fail badly) in contrast to the TRW, with its radically different, indeed opposite, type of subwoofer technology.

B. Fundamentally Opposite Kinds of Subwoofers

A key reason we went to great lengths, discussing above how the TRW is fundamentally opposite to conventional subwoofers, was to make it clear that the TRW is not just another rung up the same ladder -- as the ever bigger and better conventional subwoofers have been, when they succeeded one another as highest on the ladder. The TRW employs a wholly different, radical technology for subwoofers.

And the key to the TRW's unique advantages, and sonic superiority, and lack of handicaps in handling low bass frequencies, is that the TRW's different technology is not only radical, but also inherently opposite to the fundamental technology of conventional subwoofers, so that the TRW's technology intrinsically handles, with effortless ease and with great energy, key subwoofer tasks that are difficult or impossible for conventional subwoofers.

There have been many review articles (including ours) praising past conventional subwoofers as the best yet, many reviews using descriptive words similar to the words we're using here to praise the TRW. Why should you believe these same descriptive words now, any more than these words were believable then when applied to conventional subwoofers, but are suddenly inapplicable now to these same conventional subwoofers?

Several reasons. First, we directly compared the TRW sonics to one of the very best conventional subwoofers, representing the pinnacle of conventional subwoofer technology, and the sonic differences and contrasts were more than night and day.

Second, the sonic differences were not merely a matter of degree, with the TRW merely extending deeper in bass frequency and playing bass louder (which it does do) - rather, the TRW also gives you a whole different kind of bass experience, and (as we'll see below) a whole different kind of musical experience.

Third, reviewers and audiophiles alike have had to accept over the years that the sound of conventional subwoofer bass was the best bass that audio reproduction technology could produce. We heard and praised incremental improvements in this same type of reproduced bass over the years, as being further rungs up the same ladder. But now, even a brief listen to the TRW makes it obvious that this is a whole new kind of bass reproduction, sounding dramatically different from even the best conventional subwoofers, and sounding much more like real live bass (for those who know the sound of live bass sounds). Suddenly, with this dramatic sonic contrast, so obvious in direct comparison, our ears become instantly educated, that a whole new kind of bass is possible from reproduction systems, and that the old fashioned kind of bass we had to live with and accept before, from conventional subwoofers, is hopelessly inadequate, and actually sounds very wrong, in the many ways we have chronicled here for you (so that you too can learn about this wholly new kind of bass).

Fourth, as we've learned from the extensive discussion above, the TRW technology is so fundamentally opposite to conventional subwoofer technology, in so many ways, which allow the TRW to inherently handle a subwoofer's responsibilities so capably, that there's no way that conventional subwoofer technology can catch up to or approach the TRW's wholly different, dramatically superior sonic performance.

It literally is a whole new ball game. And all conventional subwoofers, even future designs, will still be limited to the intrinsic physical handicaps and roadblocks of their technology.

C. TRW Reduces Boom from Other Woofers

Incidentally, it's worth noting that, on the above cannon shots, adding in the TRW not only added sonic information that made the cannon shot sound and feel far more accurate, but it also seemed to effectively subtract out acoustic information, seeming to reduce the audibility of the conventional subwoofer's wildly flapping ringing misbehavior. The conventional subwoofer was still wildly flapping, as we could see visually, since it was still being driven by the same signal, but the sonic garbage from this misbehavior seemed reduced when we added the TRW into the system.

How could this be so? We hypothesize that the huge, continuing, correct positive pushing pressure from the TRW, as the cannon shot's explosion signal continued to push positively, acoustically swamped (in room pressure), and thereby offset, the smaller negative sucking sound of the conventional subwoofer's ongoing ringing, during the negative portions of its negative overshoot (region 2) and ringing (region 3). In effect, the TRW with its huge positive DC energy was biasing the large (but smaller) AC ringing misbehavior of the conventional subwoofer, raising it upward so that this AC ringing stayed entirely positive (class A instead of class B, if you will).

And it makes obvious sense that a signal that stays positive, as it should from this cannon shot, sounds more accurate and less spuriously garbagy, even if it does vary somewhat in its positive amplitude, than a signal that rings between positive and negative, alternately pushing air into the room and sucking air out of the room, as the conventional subwoofer does via its misbehaving spurious ringing, when used alone without the TRW. We'll see below two further examples where the TRW's huge energy, DC biasing ability provides yet further sonic benefits.

D. Music

Again, we'll start with the most obvious, expected sonic differences, and work toward the unexpected, which actually turn out to be of even greater sonic benefit, to even more of your music.

D.1. Pipe Organ

First out of the gate was of course a pipe organ recording, the famous Vikings track from the Reference Recordings' CD Pomp and Pipes. Organ notes are similar to sine waves, so they can elicit and probe different bass performance aspects than transient signals do (our further sonic tests below employ transients). Some organ pipe notes on this track are very low in frequency and very high in bass energy. Through just the state-of-the-art conventional subwoofers, these organ notes sounded quite powerful and impressive, as good as we've ever heard them from conventional subwoofers. But, with the TRW added, these same organ notes took on whole new qualities and dimensions. Yes, these notes went even deeper and were even more powerful with the TRW, by a dramatic margin. But, even more impressively, rather than merely hearing the bass and slightly feeling the bass, as happened with the conventional subwoofers, with the TRW added your whole body shook with the bass, as though the organ pipe were vibrating the very planet and the entire atmosphere.

Furthermore, with the TRW the quality of the organ pipe's bass became entirely different, and much more true to life. A large organ pipe moves a huge volume of air, but at very low pressure. The TRW makes bass energy in this same way, so the TRW accurately replicated this same bass quality, with the same relaxed effortlessness that the giant organ pipe itself evinces. The giant organ pipe can afford to be relaxed, even while it is producing a huge amount of bass energy, precisely because it is so large, and the TRW can do the same, since its effective radiating diaphragm area gets so large at low bass frequencies.

In contrast, the conventional subwoofers created a wholly different kind of bass quality for these organ pipe notes, the high pressure sound of a small volume pump madly pumping as hard as it can, and this sonic quality is all wrong for pipe organ bass, and indeed is all wrong for virtually all bass musical instruments. Anyone who has heard these bass musical instruments live can instantly hear this dramatic difference in bass quality, and can instantly recognize that the TRW is very right, whereas the conventional subwoofer is very wrong.

D.2. Plucked String Bass

Our next musical test was a plucked string bass, as heard on Midnight Sugar (Three Blind Mice) and on Red Mitchell, Home Suite (Caprice). Now we're testing with transients, which constitute the bulk of all program material, and which demand good subwoofer performance in the time domain as well as the frequency domain (sine waves and pipe organs are less demanding, only demanding good performance in the frequency domain).

With the TRW added, the bass plucks had a much more solid foundation, as though they were grounded and rooted in the earth itself. In contrast, with the conventional subwoofers alone, the bass plucks sounded more superficial, without a solid foundation. Also, the resonance of the bass viol's huge wooden sounding board and cavity was reproduced by the TRW with the correct bass quality, again the effortless, low pressure bass that a large diaphragm produces. In contrast, the bass quality from the conventional subwoofers alone again had that forced, high pressure quality, totally alien to the actual bass sonic quality produced by a live plucked bass.

The biggest sonic surprise, with the plucked string bass musical selections, were the sonic differences in boominess vs. tightness, and bass definition. Since the organ notes above were essentially steady sine wave tones, they did not probe or reveal the transient response differences between the TRW and conventional subwoofers. But the plucked string bass is indeed a transient, so the differences in bass transient (time domain) response, between the TRW vs. the conventional subwoofers, came to the fore and became sonically very important.

With the conventional subwoofers alone, the transient response sounded decent enough, as good as we have heard from other conventional subwoofers, but in direct comparison to the transient response with the TRW added, it was obvious that the conventional subwoofers were still very boomy, loose, woolly, and poorly defined in their transient response, with lots of lingering overhang. We have come to accept this kind of poor transient response and sound from our subwoofers, because we have never heard anything really different or really better. But, with the TRW added to the system, bass transient response took on a whole new character on these plucked bass notes, a character that was obviously far truer to the actual sound of live plucked bass, with vastly better tightness, definition, and absence of artifacts like overhang and boom. Suddenly the plucked bass sounded real and live, not like an artificial hi-fi system.

It's interesting to note that the TRW achieved this dramatic improvement in bass transient response when merely added to the system, with the conventional subwoofers still playing as before. We suspect that this is another example, where the TRW's huge acoustic output, of the correct transient signal which goes down to DC, acoustically overwhelms and offsets the boomy, ringing, higher frequency AC misbehavior from the conventional subwoofers. Of course, the tight definition and lack boom, in the system's bass transient response, would naturally be improved even further by leaving the TRW in but taking the conventional subwoofers out, and this is precisely what we did for our second round of listening tests, discussed below.

D.3. Piano

The third musical test employed piano notes with dynamic attack, such as on that Midnight Sugar track. These piano notes have largely midrange and treble spectral energy, so we are moving up the musical scale, from the bass organ notes and the bass notes of the plucked bass viol of our previous comparisons. Because the piano is a percussion instrument, the attack of each note is a singular transient, and therefore actually contains spectral energy down to DC, even though the sustain of the note is nominally in the midrange or treble. Thus, in theory at least, the extent of the TRW's reach down to DC, and its full energy and accurate transient response down to DC, should be of some sonic benefit. But what exactly would these theoretical sonic benefits actually sound like, if audible at all?

With the TRW added, each piano note became much more solidly grounded, since it now had a solid low frequency foundation for the whole note, in the low bass content actually contained in the attack transient.

Also, since each attack transient, even for high frequency piano notes, contains infinitely dense spectral energy all the way down to DC, it excites the resonances of the piano's huge wooden sounding board, which can clearly be heard from a live piano. With only the conventional subwoofers playing, we heard each strike transient of the hammer hitting the metal piano strings, but we could not clearly hear the piano's wooden sounding board at all. But, with the TRW added, the sonic contribution from the piano's sounding board was clearly evident. Moreover, this sonic contribution had all the right sonic qualities, to sound just like a live piano. With the TRW, the sounding board clearly had a natural wooden sound, which nicely and naturally counterbalanced the steely sound from the hammer attacking the metal strings. And, with the TRW, the powerful energy emanating from the huge sounding board had that effortless, relaxed quality that naturally comes from a large diaphragm radiating low pressure acoustic energy.

Some of the sonic benefits, realized by the TRW on these midrange and treble piano notes, were quite unexpected. Each note became much more coherent, much better focused in time, with all parts of the note and all parts of the spectrum sounding together. And, with all parts of each note's energy cohering in time and being focused at the same time, the piano's dynamic range also increased dramatically, with a much higher crest factor.

How and why does the TRW achieve these further sonic benefits? All conventional subwoofers, with their high reactances at low frequencies, are inherently dispersive, scattering the energy of the transient attack to different, erroneous phases and to various different points in time. But the TRW is inherently free of reactance at low bass frequencies, so it does not scatter this transient energy over time, and instead plays it all at the same time, so it coheres in time, with far superior focus and dynamics.

Additionally, with its far superior reach to DC, the TRW takes the very low frequency spectral energy actually contained in the piano's attack transient, and plays it at the correct full level, for the correct long duration, without declining (as conventional subwoofers do in region 1), and without negative overshoot that cancels (via sucking) the positive pushing energy (as conventional subwoofers do in region 2), and without the spurious ringing that effectively cancels itself out with alternate pushing and sucking (as conventional subwoofers do in region 3).

Thus, the TRW achieves and reproduces the correct pedestal or foundation, at full correct amplitude and for the full correct duration, that is required to support the midrange and treble spectral content of the piano note, and is required to reproduce the correct sonic waveform for the whole piano note, including all its spectral portions. With the TRW, the piano became a solid, three dimensional, palpably real entity in front of us, even on an upper frequency note that one might think would not involve a subwoofer at all. Without the TRW, without the pedestal and waveform accuracy on this same upper frequency note, the same piano sounded instead like a non-solid, two dimensional phantom being artificially reproduced by some hi-fi system.

Note too that the deep bass content of the initial attack transient, the pedestal foundation for the whole note, actually lasts for the entire temporal duration of the whole note, including the sustain temporal portions with midrange and treble content, and it lasts so long precisely because it is and represents such low frequency information. Therefore, the low bass content of the initial attack transient actually becomes a crucial pedestal and foundation for the whole piano note's waveform, not just for the initial attack temporal portion.

D.4. High Frequency Violin Pluck

Continuing to move up the frequency spectrum, our last musical test was those high frequency violin plucks, such as those a little over a minute into the fourth movement of Bartok's Fourth String Quartet (Chilingirian on Chandos). A violin, in contrast to all the previous musical instruments, has small dimension, with a small sounding board and small cavity. Thus, these elements would not be producing any low frequency information to speak of.

But what about the attack transient of the pluck of the high frequency string itself? Theory tells us that this attack transient actually contains spectral energy all the way down to DC, and our measuring microphone confirmed this. But there's only a small amount of spectral energy at very low frequencies. So of course we had to find out if perchance the TRW would make any perceivable sonic difference on this high frequency violin pluck, when added to massive conventional subwoofer systems that already boast full response down to 16 Hz.

And our desire to test this was more than idle curiosity. Because, if the TRW made a sonic improvement even on this high frequency violin pluck, that would mean that the TRW is musically important and beneficial for virtually all music, at all frequencies, since virtually all music involves transients.

The TRW did indeed improve the sound of these high frequency violin plucks, and everyone in the room heard these improvements. The most obvious sonic improvement was that the pluck became much more solid tactile, and believable. This was probably because the low bass energy of the initial transient acquired with the TRW the correct waveform, to become the correct pedestal for the high frequency portion of the overall waveform, so it thereby made the overall waveform perceivably more accurate, and more coherent and focused. The high frequency violin pluck with the TRW sounded much more like a real violin pluck, on a solid, tactile, three dimensional instrument you could reach out and touch, while without the TRW it sounded like a typical artificial hi-fi reproduction, with a more phantom-like, less palpable existence.

E. Extreme Makeover, TRW Edition

Finally, adding the TRW brought even further sonic improvements that were a complete surprise. The following surprising benefits were heard on all kinds of music, at all frequencies, including midrange and treble frequencies. The same benefits were heard by everyone in the room, and they were consistently heard as, in disbelief, we repeatedly switched he TRW in and out of the system, shaking our heads at these surprising sonic improvements we kept hearing.

Without the TRW, the system sounded like a great quality but nevertheless artificial hi-fi reproduction. There was some sense of strain at midrange and treble frequencies, some artificial hard glare at these frequencies, some temporal smearing of what should be individuated and articulated details, some loss of transparency and of black intertransient silence from the fact that the temporal smearing of energy created masking and filling noise at the wrong time, and some phony brightness at these upper frequencies.

These are all sonic symptoms of distortion. And they all magically disappeared when we switched the TRW back in. It was as if the TRW waved a magic wand over the sonics of the whole audio system, did an extreme makeover, and gave us a whole new audio system. Here are the specific improvements we all heard.

With the TRW included, the sense of strain disappeared, including at midrange and treble frequencies, and the music emerged naturally and effortlessly.

The artificial hard glare disappeared, this change sounding almost as though we had changed from a mediocre solid state power amplifier to a great tube power amplifier, for the system's main loudspeakers. Musical instruments sounded warmer, mellower, more natural, and far more realistic, far more like the sound of real live instruments and far less like artificial hi-fi reproduction.

The temporal smearing disappeared, and details became much better individuated and articulated, but without any artificial sharpness. With the disappearance of the temporal smearing, high frequency details and transients became much more focused, coherent, and dramatically faster, while also actually becoming more delicate (which is a sure sign of true speed, since each transient declines quicker after its peak, hence is over with sooner, hence sounds more delicate).

Also, with the disappearance of temporal smearing, black intertransient silence improved, and overall transparency and clarity dramatically improved, since there was no longer spurious noise energy (from the temporal smearing) obscuring musical details and filling in what should be the black background silence, against which musical details should be audible in clear relief.

Finally, the phony excess brightness also disappeared, resulting in a much more musically natural tonal balance and sonic quality.

As one example of the above sonic contrasts, a hard strike upper frequency piano note, played on the system without the TRW, sounded strained, with artificial glare and excess brightness, and we could hear only the metallic sound of the strike and the glare. When we added in the TRW, the same piano note sounded natural and relaxed, without strain, and the artificial glare and excess brightness and excess metallic quality all disappeared. And, with these spurious distortion artifices gone, the whole system became more transparent, so for the first time we could clearly hear the subtle, true to life sounds of the wood and the felt materials in the piano hammers, as they struck the metal strings. Suddenly, with the TRW, the piano sounded physically and musically real, as an instrument that actually uses wood and felt and metal to make its sounds, not just metal (as the system without the TRW sonically suggested).

E.1. Puzzle about Possible Cause

Now, the TRW is a great subwoofer, as we have seen, and more. But how on earth could the TRW, or any subwoofer, operating only at low bass frequencies, be of such broad sonic benefit, and at midrange and treble frequencies, when merely added to a system?

The midrange and treble frequencies (as well as the upper bass) came from the main loudspeaker system, driven by their own dedicated power amplifiers. But these components could not be the direct agent, of the distortions we heard and the many adverse sonic consequences therefrom.

Firstly, these components are the very best of their kind available, and are known for their enormous dynamic capability with low distortion, so they could not directly be the source of strain and distortions we heard, at what were merely moderate listening levels (the power amplifiers were Krell monoblocks).

Secondly, regardless of the capabilities of these main system components, the bald fact was that they were still playing exactly the same signal at the same level when the TRW was merely switched in or out of being added to the system, so their internal behavior could not possibly have changed, to in any way be directly responsible for the many and dramatic sonic changes we heard. And, again, we all heard these same changes, we repeatedly heard them, we heard the same changes on many kinds of music, and these same changes remained consistent in character for all kinds of music.

We next checked out the electronics chain, in case some subtle second order effect was causing these sonic changes. But this double check failed to reveal any possible spurious explanation.

For example, the TRW was switched in and out by merely rotating its input volume control, and there is a buffer stage before this volume control, isolating this volume control from previous electronics in the chain. Thus, there could not be a subtle change in loading (say nonlinear loading) upon the previous electronics in the chain that could conceivably affect the signal.

Furthermore, the system's electronic crossover has separately buffered outputs for its output feeding the TRW and its output feeding the main signal to the main loudspeakers, so there is no way that any change in one leg's loading could affect the signal going out the other leg.

E.2. Plausible Explanation of TRW Magic

So that leaves us with only one possible explanation. As Sherlock Holmes wisely said, whenever you have eliminated all other possibilities, then whatever hypothesis remains, however implausible, must be correct. Actually, it's not so implausible, since we have already noted several examples of the same phenomenon with the TRW in the above discussions.

In the above sonic comparisons, there were two concrete examples, the cannon shot and the plucked bass viol, where the TRW, when added to the system, effectively overwhelmed and offset the spurious ringing of the misbehaving subwoofers. Then, in our earlier discussion of the physical handicaps plaguing conventional subwoofers, we discussed how their region 3 ringing could cause FM distortion of all music, at all frequencies, as detected by the ear. Now, all we have to do is put these two concepts together. Presto! We have a plausible explanation of this seemingly strange phenomenon, whereby merely adding the TRW makes the whole system sound, at all frequencies, cleaner, clearer, and more natural, just as we in fact kept hearing.

Recall that virtually all music keeps changing, and is therefore composed of transients, especially singular transients that do not identically repeat themselves. All transients actually contain spectral energy to extremely low frequencies, approaching DC. Therefore all musical transients stimulate the region 3 spurious ringing of conventional subwoofers, which is triggered whenever there is spectral energy at the subwoofer's resonance frequency or at any lower frequency. This region 3 conventional subwoofer spurious ringing, stimulated by all musical transients at all frequencies, creates Doppler or FM sidebands in the room air, around every musical sound, even those musical sounds at midrange and treble frequencies. The human ear's inherent nonlinearity then acts as a detector of these sidebands, turning them into full fledged FM distortion. It so happens that FM distortion has all (and exactly) the various adverse sonic properties and consequences we reported hearing above, when the TRW was not included in the system.

Presto! A plausible explanation of the various distortions and consequent other sonic degradations we heard from the system without the TRW.

We have come to accept these distortions as part of the hi-fi experience. But, when the TRW is added to this system, and we suddenly, in direct comparison, hear the system without these distortions, then those distortions become obvious, and become unacceptable. When we hear how the system is so much cleaner, clearer, faster, more articulate, and more musically natural with the TRW, then the system without the TRW suddenly is revealed as having been artificial hi-fi, instead of real music.

And what exactly is the magic by which the TRW achieves this change?

Simple. The TRW is simply doing the same thing that we already saw it doing above with the cannon shots and the plucked bass viol. The TRW's added contribution, that is so very accurate at low bass frequencies, reproduces correctly, in the time domain, the low bass content of each and every musical transient. Because that low bass content extends down to DC for most musical transients, the low bass content of the signal, and the accurately tracking TRW, stay positive for a long time (relative to the time frame of the midrange or treble musical transient).

So the TRW stays positive, even while the conventional subwoofers are ringing and alternating between positive and negative air pressure, thus creating those FM distortion sidebands. And, because the TRW can put out such a huge amount of low bass energy, far greater than conventional subwoofers, the TRW's positive pushing, nearly DC contribution overwhelms and offsets the misbehaving conventional subwoofers' ringing AC contribution. Additionally, the TRW's nearly DC contribution, staying positive, biases the positive and negative swinging output from the ringing conventional subwoofers, so that the net total acoustic pressure in the room never swings negative. Thus, the TRW effectively overwhelms the distortion sidebands created by the misbehaving ringing of the conventional subwoofers.

Presto! We now have a plausible explanation for all the things we heard, for the totally unexpected sonic magic that the TRW can wreak upon the total system sound, at all frequencies.

F. The TRW without Other Subwoofers

In our sonic listening testing, we next repeated all the musical selections, but this time with a different test setup. The TRW was the only subwoofer employed, and there were not any of the conventional subwoofers in the system. We simply listened first to only the main loudspeakers, which had excellent response down to 40 Hz, and then repeated the musical selection with the TRW switched in. We had several reasons and goals for this alternative protocol.

In the previous setup above, the base system was already a full perfectionist dream system, complete with three massive state-of-the-art conventional subwoofer systems. And it was important for us to sonically discover what the TRW might be able to achieve even beyond the best conventional subwoofers, when added to this system. But the vast majority of us will not already have three giant subwoofers in our system and be adding the TRW as a fourth. Most of us will want (or can afford) only one subwoofer, added to our main loudspeakers, which will have good response down to at least 40 Hz and perhaps to 30 Hz, but not much below. So it behooved us to also evaluate the sonics of the TRW when added only to main loudspeakers, as the only system subwoofer.

Furthermore, we had nagging doubts that some of the TRW's tightening of bass transient response, noted above, might have been due to spectral overlap with the three conventional subwoofers, combined with a fluke of temporal misalignment, whereby the TRW's bass contribution was out of phase with, and thus partially cancelled, the boomy output of the conventional subwoofers. By eliminating the other subwoofers entirely from the picture, and by also eliminating any spectral overlap with the woofer of the main loudspeaker system, we could better assess the sonic qualities of the TRW's bass contribution on its own.

Additionally, even though the measured response of the TRW-17 does extend up to 40 Hz, there are good reasons (discussed below) to limit its high frequencies at about 25 Hz. So, on behalf of all of you who would want the TRW as your only subwoofer, and would want to combine the TRW with full range loudspeakers that, to cite the worst case scenario, might go down only to 40 Hz, we wanted to find out what the TRW would sound like, as the sole subwoofer, when we deliberately simulated this worst case scenario, by purposely leaving a 15 Hz gap in the system response, between the 25 Hz upper limit the TRW was set to and the 40 Hz lower limit that the main loudspeakers were set to. Since we also wanted to sonically test the sound of the TRW without possible contamination from any spectral overlap, we could kill two birds with one stone, by deliberately listening with this 15 Hz gap.

The results of this second sonic testing phase are easy to summarize. First, all of the TRW's sonic virtues and benefits cited above were still very evident, and still sonically amazing.

There was of course less ringing boom for the TRW to overcome, since the conventional subwoofers had been deleted. But some ringing boom was still evident from the woofer of the main loudspeaker system, and the TRW was still very effective at acoustically quenching this, to give us that same tight, impactive, well defined bass from the whole system that it had before. Note that here, because there was virtually no spectral overlap, it became clear that the TRW's sonic benefits, not only in being tight itself but also in reducing the lingering boom from the main loudspeaker's woofer, must have been due to the DC pedestal and positive acoustic biasing mechanism discussed above, and not due merely to happenstance phase misalignment and cancellation.

The sonic magic that the TRW wrought before, in making the whole system sound cleaner and clearer and more musically natural, even at midrange and treble frequencies, was still very obvious in this new system setup. If our plausible hypothesis above is correct, this means that the conventional woofers of the main loudspeaker system also create significant FM distortion, acoustically in the room, with their spurious ringing (these FM distortion sidebands would be slightly farther out, since the main loudspeaker woofer rings at a higher frequency or pitch than the conventional subwoofers did).

Our most important new finding, from this new system setup, was that the TRW-17 integrates superbly with main loudspeakers, as the only subwoofer in the whole system. Spectral coverage sounded seamless and natural, even with the 15 Hz gap that we had deliberately left in the system response. It is a well established fact that the brain automatically, subconsciously fills in these kinds of spectral gaps, especially on familiar types of sounds (music or voices or sound effects). The brain does this exceptionally well, literally synthesizing the missing information to fill in the gap, when there is accurate information both below and above this spectral gap, as there is here (especially with the TRW's superb waveform accuracy). Thus, there is good scientific reason for the superbly seamless integration we heard between the TRW and the main loudspeaker, even with the 15 Hz gap.

Our experimental finding here, backed by good scientific basis, means that you can confidently use the TRW as your only subwoofer, even if your main loudspeakers do not extend any lower than 40 Hz.

Part V: Practical Considerations

A. Enclosure Box

Hoffman's iron law dictates that the very best, most capable conventional subwoofers come in huge enclosure boxes, which make a huge imposition into your listening room (examples are the Wilson XS and Avant Garde subwoofers). The TRW extends far, far lower in bass than any conventional subwoofer, and can move far more air and play much louder. So it would be reasonable to assume that the TRW comes in an even bigger box enclosure, which makes an even bigger intrusion into your listening room.

But it doesn't. In fact, the TRW doesn't come in any box enclosure at all. Moreover, the TRW does not intrude into your listening room at all.

How can this be? Has the TRW, along with its radical technology that's the opposite of conventional subwoofers, also managed to reverse the laws of physics and acoustics? No. You just have to think big. Really big.

As discussed above, the TRW's bass performance is in a whole different class than even the best conventional subwoofers, and indeed is unique. The TRW is unique in the quantity of bass generated, both in terms of low frequency extension and also in terms of energy loudness. The TRW is also unique in the quality of bass generated, both in terms of accurate transient (time domain) response and also in terms of accurate low pressure bass sound. One of the keys to all this TRW performance is the fact that the TRW can move huge volumes of air. But, in order for the TRW to be able to move huge volumes of air, its fan must have unfettered access to huge volumes of air. That's why the TRW, for optimum performance, requires a huge box enclosure, much larger than even the largest enclosures employed by conventional subwoofers. The laws of physics and acoustics dictate that it needs a huge volume of air to work with, which means a really huge enclosure. Also, the TRW extends extremely low in bass frequency, which corresponds to extremely long wavelengths, which means that any enclosure should have very large dimensions.

How then could one come up with a large enough enclosure box for the TRW? Simple. Think outside the box (sorry). How does the TRW manage to come into your house, without bringing along a huge box enclosure that intrudes into your house space? Rather than bringing an enclosure box into the house, instead the TRW simply uses the house itself as an enclosure, a really big enclosure.

Fortunately, most of our houses have handy just such a huge volume, that is substantially unused. The TRW fan is installed in your house's attic, basement, or garage, whichever is conveniently close to your listening room. The TRW employs that whole attic, basement, or garage space as its enclosure box, faced by the back side of the fan driver (just as an enclosure box is faced by the back side of a conventional subwoofer's cone driver). And, from that location near your listening room, the front side of the TRW fan driver is ducted into your listening room via a vent in the wall or ceiling. Thus, the TRW subwoofer does not intrusively take up even one cubic inch of listening room space. And its workings are hidden away in an unused space within your house's shell.

The TRW uses this house enclosure box as an infinite baffle closed box. Ideally, the volume of this infinite baffle closed box should be as large as possible. In fact, the TRW works wonderfully if its fan is installed in an outside wall of your house, such that the back side of its fan actually faces the infinite volume of the great outdoors as its "enclosure box". One installation tried this, and the sound was great inside the house. The only problem was that, even with the TRW subwoofer's huge acoustic output at very low frequencies being quickly dissipated in the great outdoors, neighbors several blocks away began complaining that their dishes, apparently possessed by the devil, were on occasion mysteriously dancing about on the shelf. Of course, if you live on an isolated farm, you can go for this simple approach. For most of us, the most practical installation of the TRW will be in an attic, basement, or garage, any of which should have sufficient volume to be a good enclosure box.

What happens if your house does not have an optimally large attic, basement, or garage that is conveniently close to your listening room? What happens if you have to employ a smaller house space as a back enclosure? With conventional subwoofers, if you use an enclosure box that is too small for the given subwoofer driver, the system resonance frequency goes up, and so the subwoofer system does not extend as low in bass frequency.

Interestingly, this engineering rule does not apply to the TRW. Because the TRW employs a fundamentally opposite technology than conventional subwoofers, the TRW does not have reactances at low bass frequencies, and is inherently a DC device rather than an AC device. Thus, the TRW will still have full response down to DC, and will retain its superb bass quality, even if your house geometry forces you to install it with a backside enclosure volume that is smaller than recommended.

The only TRW performance aspects you would sacrifice, by employing a smaller than recommended volume for the backside enclosure, would be efficiency and maximum possible loudness level. And the TRW has plenty of extra margin in both these performance aspects, so you can afford to sacrifice somewhat in these parameters, if need be.

B. Listening Room Contribution

Since we're now looking at really big volumes, it behooves us to also examine the volume of the enclosure box on the front side of the TRW fan, which is of course your listening room. Here, on the front side of the TRW fan, an infinite volume with infinite dimensions is not ideal. Instead, ordinary listening room volumes, with ordinary room dimensions, actually work to help the TRW's bass response.

You see, when bass frequencies go lower their acoustic wavelength in air gets longer, and, when the wavelengths get long enough to approach the dimensions of the listening room, the boundary surfaces (walls, floor, ceiling) of the room then begin to reinforce the acoustic energy in the room, making it stronger. This is an acoustic phenomenon that happens in the room and the room air, after the acoustic energy has left the radiating woofer and/or subwoofer. So this boundary reinforcement phenomenon happens to all woofers, regardless of type, including the TRW.

The TRW design works hand in glove with this boundary reinforcement phenomenon, in order to benefit the TRW's performance, by giving it flat response down to DC. The TRW, being a DC device, inherently and effortlessly extends all the way down to DC. But that extension to DC does not automatically mean that its frequency response is actually flat at these very low bass frequencies. The manufacturer's measured frequency response curve for the TRW-17, measured in a real listening room, is indeed flat, and flat down to DC. But the TRW relies on the boundary reinforcement phenomenon, present in all real rooms, to achieve this flatness of response. In other words, the TRW is designed to have flat frequency response in real rooms, which of course is how you will be listening to it.

If, on the other hand, you were to listen to the TRW radiating hypothetically (say) into the open air outdoors instead of into a real room, then the TRW would still extend effortlessly down to DC, but the curve of its response extending down to DC would not be a flat curve, and would instead have a very gradual, shallow declining slope, probably at 6 dB per octave. Why? As discussed briefly above, the TRW's radiation resistance declines far more gently, at lower frequencies, than conventional subwoofers, being a mere linear decline rather than the square law decline faced by conventional subwoofer drivers (the TRW achieves this shallower decline because of the fact that its effective diaphragm area increases, linearly, with lower frequency). But a decline is still not flat, so this gentle decline in radiation resistance, with lower frequency, would mean that the TRW's frequency response should decline gently, with lower frequency, if played into the open air outdoors. However, when playing into a real room with boundaries, the boundary reinforcement phenomenon boosts the acoustic energy in the room at very low frequencies, so the TRW's frequency response curve becomes essentially flat.

Each listening room has different dimensions, and thus a slightly different characteristic for this boundary reinforcement phenomenon. The TRW system includes a parameter adjustment that can customize the TRW's performance, so that it matches your room dimensions, in order to achieve the flattest possible frequency response, when working with your particular room's boundary reinforcement parameters. Interestingly, this TRW adjustment parameter actually tailors the high frequency end of the TRW's spectral range, and does not do any equalization of the low frequency portion of the TRW's spectral range. We mention this because, with conventional woofers and subwoofers, when equalization is employed it is applied at the low frequency end, which causes all kinds of further problems (with excess excursion, further degrading of transient response, etc.).

It's also worth noting in passing that, if the TRW were used outdoors instead of into a real room, and if its frequency response curve did thereby decline, then the TRW would still have excellent time domain transient response, hence excellent bass quality. That's because its rolloff slope would be very shallow, a mere 6 dB per octave, and bass systems with this very shallow rolloff slope still have essentially perfect time domain transient response, with no negative overshoot and no ringing. In contrast, all conventional subwoofers roll off at much steeper rates, with slopes twice as steep or worse (12 to 36 dB per octave), which, as we discussed above, is why they evince such bad spurious misbehavior in their time domain transient response, i.e. in their actual performance in real time.

C. Fan Installation

You'll want to hire a qualified carpenter or contractor, to do the planning and installation work for the TRW fan. The TRW's manufacturer offers design consulting services for hire, to help your contractor with the planning, especially useful if your house has an unusual configuration.

If your listening room is immediately adjacent to your attic, basement, or garage, you might think that one could simply install the TRW fan in the listening room wall leading to that other space, thereby using the listening room wall as the mounting baffle for the fan. But it's better to actually install the TRW within that other space, on a baffle stretching across that space, near your listening room wall. This creates a chamber in front of the TRW fan, this chamber still being within your attic, basement, or garage.

This chamber is then lined with sound absorbing material, which absorbs any unwanted high frequency noise from the whirring fan, before it reaches your listening room, while not absorbing any of the desired low frequency bass output from the fan. This chamber then in turn leads into your listening room, say via a large vent cut into the wall, ceiling, or floor (this vent can of course be covered with an attractive grille or cloth of your choice).

The TRW fan, with its constant rotation, naturally makes a whirring sound, much like pink noise, just as every fan does, so its best to absorb and quiet this noise before it reaches your listening room (on the other hand, home theater devotees are already accustomed to living with projector fan noise, so the TRW's background fan noise might be tolerable for them if heard directly).

Then, if you want to play the TRW really loud, its fan blades go to a steeper pitch, and this creates air turbulence around the fan blade tips, a turbulence which sounds just like the air turbulence created by a bird flapping its wings (note that it is not the fan blades themselves making the noise, nor are the bird's wings actually creaking and directly making the noise, but rather it is the air turbulence itself that makes this noise). Thus, if you want to play the TRW really loudly, there's a second reason to put a chamber with sound absorbing material between the fan and your listening room. On the other hand, if you are like me, and are more impressed by quality of bass rather than sheer quantity of bass, then you might wind up playing the TRW at lower volume levels that don't engender this fluttering air turbulence sound, so you might have less need for that front chamber with sound absorbing material.

D. High Frequency Limits

Subwoofers are of course not designed to play high frequencies, and all subwoofers have high frequency limitations. With conventional subwoofers, these high frequency limits are reached when the cone starts breaking up (the larger the cone is for better bass, the sooner it reaches its upper frequency limit due to cone breakup), and when the enclosure has an internal response peak that must be avoided by crossing over the subwoofer to the main loudspeaker at a lower frequency.

The TRW likewise has its upper frequency limits. The TRW realizes its superb, unique, fundamentally opposite bass performance because it is intrinsically a DC device. But this means it has to work a bit to be an AC device, and this work gets hard as the AC frequency gets higher. Because the TRW employs such radically different technology than conventional subwoofers, the mechanisms which impose the TRW's high frequency limits are naturally very different.

For example, the motor in the TRW, which changes the fan blade pitch, obviously has to do its changing work faster and faster as the frequency goes higher. At some high frequency point, the mass of the fan blades (and connecting mechanics) cannot be changed any faster. Similarly, at some high frequency point of back and forth changing, the fan blades will start undesirably flexing and breaking up (much like cone diaphragm breakup), instead of staying rigid to push the air. There are striking engineering tradeoffs here, since making the fan blades heavier to become more rigid would make it harder to change their pitch fast.

For another example, consider the fan's rotational velocity. As we discussed above, the fact that the TRW's fan keeps rotating at the same velocity, when the bass frequency being reproduced goes lower, gives the TRW a great advantage at low bass frequencies over conventional subwoofer drivers, which cycle ever more slowly at lower bass frequencies, since they are constrained by multitasking to track the signal.

But this same constant fan velocity is a disadvantage for the TRW at high frequencies. The TRW fan keeps rotating at the same velocity for higher frequencies, whereas conventional cone drivers in contrast cycle ever faster as the frequency goes higher (which is one reason cone driver technology is still excellent for middle and high frequencies). Eventually, at some high frequency point, the input signal is cycling so fast that it catches up to the TRW fan's rotation, and the fan blades appear, to the input signal, to be standing still in rotation. In other words, the signal is cycling so fast that the fan has not rotated significantly during a signal cycle, and thus the fan blades have not taken a significant bite of air during the signal cycle.

Thus, even if the TRW's blade pitch motor could change blade pitch fast enough to keep up with this fast cycling input signal, thereby performing its modulation function perfectly, there would not be enough airflow, from the fan's now too slow rotation, for the perfect modulation of that negligible airflow to have any effect. You can't modulate airflow in a fast cycle when there's no significant airflow within that cycle to modulate. The TRW could easily raise its high frequency limit, from this phenomenon, by simply raising the fan's rotational speed, but this would increase the fan's background noise level, and force some other design tradeoffs.

As the design of the first TRW subwoofer evolved, these design tradeoffs, which come into play at higher frequencies, were carefully balanced against one another, to produce the best high frequency extension possible, consistent with various other considerations. This first TRW subwoofer, the TRW-17, has response that measures flat up to 40 Hz, and declines above that, probably showing some of the stress that the mechanics of the fan system are beginning to experience above 40 Hz. The manufacturer recommends setting the crossover point at 20 to 25 Hz, for the signal fed into the amplifier controlling the blade pitch modulation, so that the energy fed in, up at 40 Hz, is somewhat reduced and does not stress the fan system. The manufacturer makes and sells an optional crossover and power amplifier for the blade pitch modulation, which has a built-in rolloff corner at 25 Hz, with an 18 dB per octave downward slope above that.

If you mate the TRW-17 subwoofer directly with main loudspeakers that extend down to 25 Hz, then you'll have full spectral coverage. But, as we established by our deliberate sonic experiment above, even if your main loudspeakers extend only down to 40 Hz, the TRW still sounds great, and integrates seamlessly with the main loudspeakers, and the combined system seems to cover the whole spectrum, since the human brain unconsciously, automatically synthesizes the missing 15 Hz gap in the spectrum, so you never hear anything missing.

Thus, you can confidently use the TRW-17 with main loudspeakers that extend only down to 40 Hz, as well as with main loudspeakers that might extend lower than 40 Hz. In the future, Eminent Technology might produce a second TRW subwoofer model that could be crossed over at 40 Hz, but it would have some other design tradeoffs (perhaps higher fan noise and lower maximum loudness level). In any case, our sonic experiment with the TRW-17 proves that you don't need to wait for this second TRW model, even if your present main loudspeakers only extend down to 40 Hz.

E. Cost

The TRW-17 is actually less expensive, than some of the huge conventional subwoofer systems that the TRW utterly dusts in performance. But it still is a substantial investment. Many of the parts in the TRW fan are custom machined, from expensive materials, in exotic shapes that were carefully optimized during the TRW's long design process. For example, the manufacturer had to build and try hundreds of different shapes for the fan blades, to optimize performance, since he was working in uncharted waters of radical new subwoofer technology.

This makes each TRW-17 very expensive to build, and that is reflected in its price of $12,900 for the basic fan unit. Ancillary components are modestly priced, at $350 for the motor controller, and $700 for the modulator power amplifier with crossover (you could instead use your own audio power amplifier, rated at 200 watts or more, and your own crossover).

You also should factor in the cost of hiring a qualified carpenter or contractor, to build the baffle board across your attic (or basement or garage) space, to cut in the vent to your listening room, and to actually mount and wire in the fan (Eminent Technology offers its own design services for hire, as well).

Furthermore, if you agree with us that stereo bass is important, for believably recreating the spatial imaging of a large alternative venue, you might want to consider installing a stereo pair of TRW-17 subwoofers.

The TRW subwoofer might be expensive, but it's worth every penny in the thrills and chills it will give you from your film soundtracks, far beyond what even the best conventional subwoofers can achieve.

The TRW is also worth every penny for the far more accurate, much higher quality bass it will give you from all your music recordings, as well as the sonic benefits it brings to musical transients at all frequencies throughout the spectrum (better dynamics, focused coherence, tactile solidity, etc.).

And, for me, the TRW is worth every penny, above all, for the amazing, unexpected magic wand it waves over your whole system, making your whole system sound cleaner, clearer, and more natural, making the whole system sound less like artificial hi-fi and more like real live music, apparently by curing distortions that we have had to live with and have accepted lo these many years, but from which the TRW frees us at last, forever more.

How much would you pay for an audio component that totally transformed and upgraded your whole system in these ways, giving your whole system an extreme sonic makeover?