Designing the Best Small Speaker

My design concept for the Callisto

By Roy Johnson, Designer

I approached Callisto's design with one thought: If this was to be the very best compact speaker, then every aspect of the theoretical performance from its woofer and tweeter must be extracted. A small speaker is, in many ways, more difficult to design than a large model because its output comes from just two drivers and there's so little space for acoustic absorption. Every aspect of design becomes more critical to the overall performance.

The choice of the woofer is very important for low-distortion bass and for a clear voice range. Its tweeter must be capable of blending smoothly with the woofer and have wide dispersion. The crossover circuit should be simple, for clarity and efficiency. The cabinet must be very rigid across a wide range of tones, and shaped for minimal reflection so that its presence isn't heard. Finally, the Callisto needed to be able to play very softly with full musicality and yet still deliver front-row performance on any music or soundtrack for listeners in small-to-medium rooms.

Driver selection

The first challenge was to select the woofer and tweeter. For the Callisto, it was easy to choose the same unique woofer previously used in the Continuum 0.5 and Europa.

It remains unsurpassed in its ability to play both loudly and softly because its patented neodymium magnetic structure envelopes the entire voice coil in a powerful and uniform field. Other results of this magnetic structure are very low bass distortion and complete control of the coil on large bass note excursions. This woofer also has an extended voice and treble range for the smoothest blend to the tweeter. It's efficient. Although its cone is a very rigid and light blend of carbon fibers and long-fiber wood pulp, it doesn't look 'high tech.'

Selecting a tweeter is a complicated matter. Most depend upon nearby cabinet reflections for a uniform tone balance from the high-voice range to the highest treble. However, those reflections smear the sound, especially when the music or soundtrack becomes complicated. An ideal tweeter doesn't depend upon reflections to deliver

a uniform output. Most tweeters lose their clarity when playing softly, because their suspensions seize on those microscopic motions. An ideal tweeter would have a suspension made of tissue paper (if it didn't fall apart). It would also have a rigid yet lightweight dome without high-frequency breakup modes.

Over many years of testing, we found certain tweeters met and exceeded these requirements. Some are actually designed to have no cabinet around them, or dense wool felt placed near them to absorb reflections. The Callisto tweeter is a special edition which we test and hand-match into pairs for the best performance. It also has its own large rear chamber which we damp even further.

Determining the shape

After the drivers were selected, the cubic inches required behind the woofer were determined. Computer simulations of box volumes are inaccurate for many reasons, so several test boxes were built, along with a crossover circuit very close to the final design. These steps determined the exact volume required of the box.

On top of that final test box, the tweeter -- with its almost-final crossover circuit -- was placed so that it could be positioned from front-to-rear. This placement would allow its sound to arrive at the ear at the same moment as the woofer. With all that information in hand, work proceeded on the shape of the enclosure.

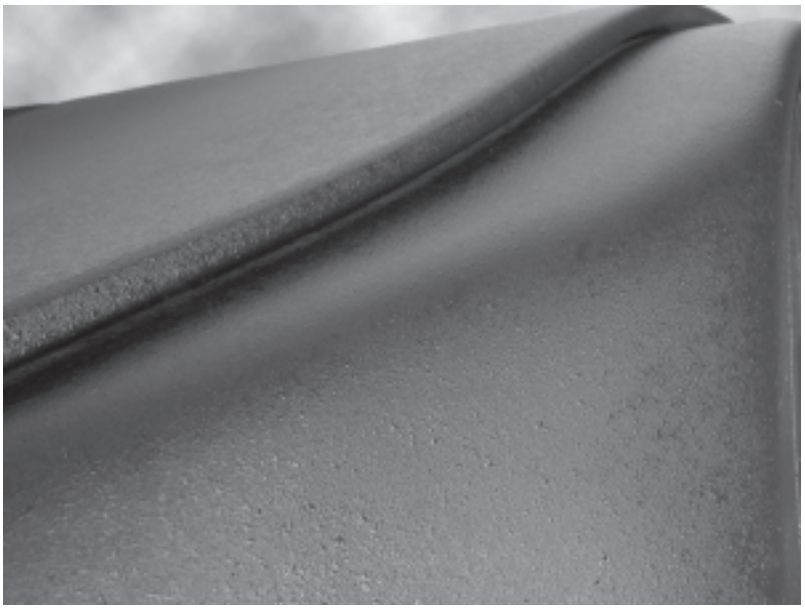
In the lowest bass, a cabinet needs to 'get out of the way' as fast as possible. Long bass wavelengths can then wrap around the cabinet to reflect off the wall behind and the floor below.

Although reflections are generally avoided in speaker design, low bass reflections return so quickly, relative to the long wavelength still emerging from the woofer, that we don't hear them as reflections. Without any walls nearby, a speaker has no bass, such as when used outdoors. With too many close walls, a speaker has too much bass. It's in-between the lowest bass and highest treble that all problems lie which make a speaker sound like one, instead of the real thing.

Since the ideal cabinet shape varies for each tone range from bass to treble, the question that needed an answer at this stage was, 'Precisely what is the right shape in each range?' After 30 years of research and testing, I developed and solved the mathematics that describe and guide the size and shape of the cabinet around each driver. This breakthrough in design was first applied to the Continuum 3 speaker. Now it was time to use it for the Callisto. Easier said than done when there's not much cabinet upon which to apply it!

The low bass range

One reason Callisto's bass ports are on the bottom is that the cabinet must be 'seen' as a small object by the wavelengths of the lowest bass so it's easy for them to move around it. As one moves up into the middle bass and into the low-voice range, it turns out that the Callisto cabinet had to be of a sufficient size to 'block' those wavelengths from instantly wrapping around it. A cabinet too large would create an 'acoustic shadow' on the wall behind it, which would change the sound of the low bass as a listener moved around the room.



The middle bass through the lower-voice range

In this range, the correct size and shape of the cabinet is most critical since a woofer will take perhaps 1/60th of a second to finish its very first outwards push.

When a cabinet is too narrow, the air-molecule collisions first begun by the woofer are free to rush around and behind the cabinet, at 770 miles per hour -- the speed of sound. By the time the woofer completes its push, those molecules are 18’ away. During that 18’ , they gain little energy from the woofer's continuing push. The audible result is a weak output in the middle bass all the way through the lower-voice range. When the cabinet is 'just the right size and shape' around the woofer, the molecular collisions gain more energy from the woofer's push. The listener hears a uniform tone balance from the lower voice range all the way down into the bass.

The middle-voice range

In the middle-voice range, only *some* sound is sent straight to the sides. It then 'refracts' off of any sharp cabinet edges. Refraction is a 'false' wave sent back to the front, when the main wave is suddenly free to expand to the rear upon reaching that edge. Other air molecules from the front naturally rush in to fill the void, and that 'negative' low-pressure rush proceeds away from the cabinet edge right back to the listener, like a smoke ring.

Careful, exponential shaping of Callisto's corners eases the transition around the edge, minimizing any refracted wave. The asymmetric-elliptical shape of its cabinet also prevents any single frequency from 'talking' to all the edges at the same instant. Middle-range sounds also travel down the front of the cabinet to reflect towards the listener. The shape of the Callisto's cabinet below the woofer was designed to spread those reflections elsewhere, so they're far less loud in any particular direction. Less 'box' is heard in the all-important voice range.

The higher-voice range and low treble

Although a woofer sends little sound to the sides in this range, the tweeter does. In the Callisto, we controlled the tweeter's dispersion to the sides so that it doesn't 'talk' much to a small room's walls. Controlling that dispersion also matches the narrower dispersion pattern of its 6” woofer for uniform tone balance to the sides. Fortunately, a particular density of wool felt, carefully placed near the tweeter, controls its dispersion immediately to the sides

and also prevents reflections off the front and the woofer's cone. Regardless, some upper-range sound still makes its way around the Callisto's cabinet. Its curved shape helps disperse those reflections so they're less audible in any one direction. Those same reflections also reach the back wall, where they'll echo subtly between the wall and speaker cabinet. The shape of Callisto's back panel helps break that reflective cycle. With the cabinet shape determined, work began on obtaining the maximum bass possible and making the cabinet as quiet as possible on the inside.

The Callisto's bass

That extraordinary woofer I decided to use generates very-low distortion bass, sufficient to fill rooms 10 to 24 ‘ wide, 12 to 30’ deep, and 7 to 10’ high -- but only with the aid of a properly-designed port. Callisto’s ported cabinet creates more low bass than a sealed one. To make the lowest bass louder, the port and cabinet volume work together with the woofer's natural resonance. A port also keeps a small woofer from stroking too far on loud, low bass notes, which distorts the vocals. The mass of air inside a port's tube is an invisible piston, literally bouncing off the air volume inside the enclosure. It's reacting to the woofer's motion, which is also bouncing off that same air volume.

Good sound depends on the woofer stopping these bounces as rapidly as possible. The woofer compresses the air in the cabinet. That pressure pushes air down the port's tube, which pressurizes one’s room. The woofer, the air in the cabinet, and the air in the port's tube form a resonating system. It doesn't take a lot of 'push' from the woofer to start the port's air into motion, nor is much push from the port required to affect the woofer.

To tightly control this resonant system, the woofer must 'communicate' to the port as quickly as possible, and the port must communicate just as quickly back to the woofer. Any time lag will result in sluggish, or 'boomy' bass. Thus, the air pressure in the cabinet must change all at once, as quickly as possible. Four parameters make this happen.

First, a cabinet's longest dimension has to be short enough so that air-pressure changes don't arrive at different times to the port and woofer.

Second, the port's intake and the woofer must both be located near the center of the cabinet, to create uniform pressure changes everywhere inside the cabinet in the shortest possible time, and to just as quickly respond to those changes.

Third, the port's exhaust and intake must be aero-dynamically shaped because the air inside its tube is oscillating at just 40 miles per hour, while the air at each end is free to move at 770 miles per hour. Any air turbulence in the transition zone at the end of the port means that the pressure is neither changing nor being communicated. Harmonic distortion, known as 'fuzzy bass,' is an unwanted result of this imbalance.

Finally, the acoustic-absorption materials inside the cabinet must be designed to absorb every sound above the port's resonance frequency and yet absorb nothing at that resonance frequency.

Each of these challenges was met in the Callisto, in 14 unique ways. Seven are new breakthroughs and patent-able technologies in loudspeaker design. Each was a result of on-going experiments begun 25 years ago.

The Callisto's bass ports exit beneath the cabinet, so the front surface below the woofer could be shaped to reduce reflections in the voice range. This location for the ports pressurizes the air in one's room more evenly in all directions, so the low-bass output is less affected by how close the speakers are placed to the walls.

Two bass ports were used instead of one, which cut in half the air velocity inside each for lower distortion. Together, they have a large combined surface area for more 'push' on the air in a room, creating a louder output. The intake and exhaust of the twin ports end in flares, each with an exponential curve, to eliminate turbulence at their mouths -- all to reduce distortion. The twin ports reach high up into the cabinet, picking up air pressure changes equally from the top and bottom.

These two ports are staggered from left-to-right and from front-to-rear, to pick up pressure changes uniformly from those two dimensions as well. The twin ports' tubes act as acoustic diffusers behind the woofer, where they deflect voice-range sounds off into the acoustic-absorption materials, making the enclosure quieter inside for more clarity in the voice range.

A unique combination of ultra-low density fiberglass and dense wool felt makes the cabinet very quiet in the voice range yet doesn't interfere with the lowest bass. The listener will hear maximum bass output from the ports. The base under the cabinet was shaped to prevent cavity resonances between it and the bottom of the speaker. Its adjustable spikes allow the cabinet to be tilted up or down for the clearest sound. Adjustability is a feature I coined Soundfield Convergence™ in 1996 and have engineered into our speakers since the Continuum 1 model.

Seen from the front, the inside of Callisto’s cabinet has an asymmetric, six-sided shape. The front and rear faces are also not parallel. These engineering considerations work together to prevent resonances from the upper-bass all the way into the voice range. In the high-voice range, fiberglass and felt absorb all of the sound.

The Callisto's cabinet walls are very thick and were molded from our new Q-Stone™ cast marble recipe for increased strength and less vibration. The difference is greater bass output and more clarity. Our Q-Stone™ is airtight, unlike wood. Pressure changes remain in the air and aren’t 'soaked up' by porous wood, so the woofer and ports communicate most efficiently.

The middle range

It’s easy to hear when a speaker has flaws in the voice range because we're so familiar with the sound of a human voice. Several factors are responsible for making the clearest possible voice range and a smooth transition from woofer to tweeter. The woofer must produce a uniform response throughout the voice range and into the low treble. The Callisto's woofer has the very rigid and light cone required for this uniform, low-distortion response. The voice coil behind this cone is also extremely light. Unique damping strips placed on the woofer's metal frame prevent high-frequency chassis resonances.

The mathematics developed for our Continuum 3 led to the Callisto's exterior shape. Like the Continuum 3, it was sculpted to reduce voice-range reflections from its surface, in all directions. The innovations inside Callisto's cabinet, along with its interior shape, port tubes, and absorptive materials all act together to very quickly absorb voice-range sounds behind the woofer, with no resonances at any frequency.

The treble

The Callisto's tweeter sits in its own sealed, cast-marble chamber. While this isolates the tweeter from the woofer's sounds, what's more important is the dense felt crushed up against the rear of the chassis so that all the tweeter's vibrations are completely damped. This patentable, engineering breakthrough is also used in our Continuum 3. The Callisto's treble is sweeter and more delicate, dynamic, and extended.

The crossover circuits

The woofer and tweeter each must handle a specific frequency range so that the sounds from each spread evenly throughout the room. If one could ask a woofer cone to also be a tweeter, then all the treble from it would project straight ahead like a very narrow flashlight beam. A listener would hear treble only from one best seat; the rest of the room would receive no treble at all. Sitting in one's chair, the sounds heard coming back from the room would be very 'dark,' or muffled. No recordings would sound 'right,' by anyone's standards. That's why a tweeter has to be small, and a woofer large -- but not too large in a two-way speaker. Our friend, the crossover circuit, divides up the musical spectrum with the goal to re-combine those signals at the listener's ear into the one original wave.

Tweeter crossover

Callisto's tweeter operates from 2850Hz to beyond 20,000Hz, which means it takes over from the woofer right in the critical "ess" and "tee" part of the voice range. Below 2850Hz, the crossover circuit gently rolls off the tweeter's lower-range response at a rate of 6dB per octave. This gradual rolloff is a by-product of the only circuit which will simultaneously send the signals to the tweeter and woofer, making them move together as one unit. The result is clearer sound.

'Time-coherent' behavior between a woofer and tweeter is very rare in speakers. It's difficult to engineer and can only come from this type of simple, first-order crossover circuit, which doesn't do well at protecting the tweeter from voices and bass. So, for time-coherent operation with the woofer, the tweeter is required to handle more power. The Callisto's tweeter exceeds that need. A tweeter must then have an extended stroke so it can move freely without distortion, which requires both a very flexible suspension around the dome and a very focused magnetic field to encompass its voice coil and control that extended motion.

We're fortunate that the Callisto's tweeter is so linear in its operation, so well-behaved, that the entire crossover circuit feeding it consists of one, super-premium capacitor. There's no printed-circuit board to add resonances and impure conductors. One end of this capacitor is crimped firmly to the 'positive' gold binding post.

Its other end is twisted and soldered to a cryogenically-cooled and high purity, oxygen-free copper (OFC) wire that runs directly to the tweeter's positive terminal. The return wire is identical and directly connected to the negative binding post. The solder we use is a new formula that sounds cleaner and clearer than any other we've used.

With these few circuit parts, no cabinet reflections, and such a low-distortion tweeter, it's easy to hear the differences made by wires, capacitors, binding posts, and solder. Can we explain the differences? Not entirely, but they're definitely audible.

Woofer crossover

The woofer in the Callisto operates from the low bass up to 2850Hz, and, to facilitate a smooth transition to the tweeter, is capable of a smooth output well past 5000Hz. The rate of rolloff at 2850Hz is, again, 6dB per octave. As for the tweeter, this is the only circuit that lets the woofer and tweeter move together. The result is, again, clearer sound. As with the tweeter, we're fortunate that this woofer is so linear in its operation and so well-behaved that the entire crossover circuit on the way to it consists of one small, Litz-wire OFC inductor to keep out the highs. A double run of 14-gauge, heavily silver-plated OFC wire feeds the woofer.

One final point about our Balanced-Phase™ 'first-order' crossover circuit. Any crossover circuit can be thought of, quite accurately, as a fork in the road for the electrical energy from the amplifier. If the energy of the voice range

cannot easily get through the woofer's inductor, then it's deflected down the path of less impedance -- through the tweeter's capacitor. If a crossover circuit can be made with only one component feeding each driver, then a very nice thing happens -- the woofer's inductor and the tweeter's capacitor can be chosen to be the opposite, or 'upside-down mirror images,' of each other, like a 'Y' adapter.

An ideal 'fork in the road' is created for the signal, since the amplifier doesn't know that either the capacitor or inductor exists. To the amplifier, only one 'path' is apparent. The measure of this is a 'flat impedance curve' for the entire speaker. This engineering allows the Callisto to appear to the amplifier much like a 4- to 5-Ohm resistor at most every frequency. It lets any amplifier deliver maximum power with the least distortion.

For the love of hearing it all

All of this work in developing the Callisto's cabinet would've been wasted if I couldn't get the separate sounds of the woofer and tweeter to re-combine into one original wave at your ear.

It's only then that you can hear all of the musicality hidden in that complex waveform, follow any artist or voice, and hear a sound effect to its maximum intensity or subtlety.

I've learned quite a bit since listening to music on a clock-radio motivated me to build my first speaker as a teenager. With each one I design, I use all of my knowledge and training to produce the very best of what's humanly possible. Our ears deserve to hear it all.