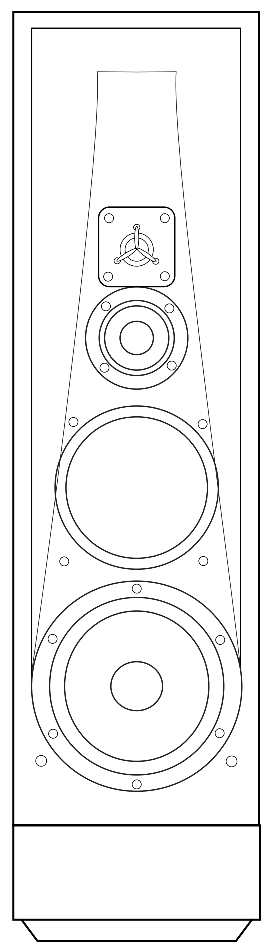
Technical Information

THIEL CS3.6

Coherent Source®

Loudspeaker



This paper describes some of the technical performance aspects, design considerations and features of the THIEL model CS3.6 loudspeaker system. It is intended to supply information for those who are interested in such matters. It is not intended to imply that good measured technical performance is sufficient to guarantee good sonic performance.

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DESIGN PHILOSOPHY

The CS3.6 is a precision instrument designed to very accurately translate electronic information into musical sound. All our efforts have been directed toward achieving extremely faithful translation of all tonal, spatial and dynamic information supplied by the amplifier.

The CS3.6 is not intended to mask or mitigate shortcomings of the recording or other components in the music playback system.

We believe this approach is the only way to provide the potential of experiencing all the subtle aspects that help make reproduced music a most enjoyable human experience.

CS3.6 DESIGN HIGHLIGHTS

- Extremely accurate frequency response: 29 Hz - 20 KHz ±1$^1/_2$ dB
- *Coherent Source* design: complete phase *and* time coherence
- Point source radiation pattern
- Very low energy storage
- Very high quality, innovative driver design

Crossover

The CS3.6 crossover incorporates 25 elements implemented with 38 components. Most of the components are used to provide a high degree of response shaping, correcting even small imperfections that are usually ignored. Very high quality components are used to ensure very low distortion levels. For example, polypropylene capacitors are used extensively and all capacitors are bypassed with custom–made polystyrene and foil units. Also, all inductors are air-cored types wound with low oxygen wire.

Specifications:

Bandwidth (-3dB)	27 - 22 KHz
Frequency response	29 - 20 KHz ±1$^1/_2$ dB
Phase response	minimum ±5°
Time response	150 µs -20 dB
Sensitivity	86 dB @ 2.8v-1m
Impedance	4Ω (2.5Ω minimum)
Recommended power	100 - 500 watts
Size	48$^1/_2$ h x 12$^1/_2$ w x 17 d inches
Weight	107 pounds

Driver Complement:

- 10" very long excursion woofer with advanced magnet system and aluminum diaphragm operates up to 500 Hz.
- 4" mid-range with two–layer, air-core diaphragm and long-gap/short coil motor system operates from 500 to 3000 Hz.
- 1" high output metal dome tweeter operates above 3 KHz.
- 10" passive bass radiator

PERFORMANCE GOALS

Since quality of musical performance is a very complex issue it is helpful to objectively identify the aspects involved. We believe musical performance can be described, with not much oversimplification, as performance in four areas.

Tonal fidelity includes overall octave-to-octave balance, the fidelity of timbres, absence of vowel-like colorations, and bass extension.

Spatial fidelity includes how wide and deep the performing space seems, how convincingly instruments are placed from the center to laterally beyond the speakers, how realistic the depth perspective is, how little the speakers' positions seem to be the source of the sound, and how large the listening area is.

Transient fidelity includes how convincingly realistic is the reproduction of the initial or 'attack' portions of sounds and how clearly reproduced is musically subtle low–level information.

Dynamic fidelity includes how well the speaker maintains the contrasts between loud and soft and how unstrained and effortless is the reproduction of loud passages.

FUNDAMENTAL DESIGN CONSIDERATIONS

In our opinion, natural spatial reproduction requires creating a realistic sound field within the listening room by mimicking the properties of natural sound sources. These properties include wide area radiation and the absence of out-of-phase energy. To meet these requirements the CS3.6 employs dynamic drivers. Dynamic drivers have the advantages of providing a point source radiation pattern with good dispersion of sound over a wide area, great dynamic capability, good bass capability and a lack of rearward out-of-phase energy. Another advantage of dynamic drivers is their small size which allows the multiple drivers to be arranged in one vertical line. This alignment avoids the problem of line source designs which must place their different drivers side-by-side, causing the distances from each driver to the listener to change with different listener positions.

The major potential disadvantages of dynamic speakers are diaphragm resonances ("cone break-up"), time errors, phase errors, cabinet resonance, and cabinet diffraction. None of these problems is a fundamental limit and all can be minimized or eliminated by thorough and innovative engineering, resulting in a speaker system without significant fundamental limitations.

TECHNICAL REQUIREMENTS

The task of engineering a speaker system requires the translation of the musical performance goals into technical goals. Although there are also many minor design considerations, the following are what we believe to be the major technical requirements that contribute to each of the musical goals.

Tonal fidelity:

- Accurate frequency response so as to not over or under emphasize any portion of the sound spectrum
- Absence of resonances in the drivers or cabinet so as not to introduce tonal colorations

Spatial fidelity:

- Point-source, uni-polar radiation
- Time response accuracy to preserve natural spatial cues
- Lack of cabinet diffraction

Transient fidelity:

- Phase coherence to provide realistic reproduction of attack transients
- Very low energy storage to provide clarity of musical detail

Dynamic fidelity:

- High output capability
- Low distortion

DESIGN GOALS

The technical requirements result in the following major technical design goals:

1. Very uniform frequency response
2. Time response accuracy
3. Phase response accuracy
4. Low energy storage
5. Low distortion

FREQUENCY RESPONSE

In our opinion the human ear is sensitive enough to the balance between component harmonics of musical sounds to detect frequency balance errors of as little as 0.2 dB if they are over a range of an octave or more. Therefore we believe that extremely accurate frequency response is an absolute requirement for a truly good speaker. Our design goal was to achieve accuracy in the design prototype of ±.75 dB with a production tolerance of ±.75 dB. The result is a tolerance in every production speaker of only ±1.5 dB and a tolerance from speaker to speaker of only ±1.5 dB at all frequencies.

Even more important than the maximum amount of response error at any frequency is the octave averaged, octave-to-octave balance which has a very high correlation with the perceived tonal balance. Our design goal was to achieve octave-averaged response within ±0.5 dB from 200 Hz to 10 KHz. Any deviation more than 0.5 dB is confined to only a narrow frequency range and therefore will have less effect on the perceived balance.

Achieving these goals requires the use of drivers with exceptionally uniform responses, drivers with very high consistency (so that few units need be rejected), drastic reduction of usual cabinet diffraction which causes response errors, and an unusual degree of compensation in the electrical network of even minor driver response anomalies.

Driver Response

The major cause of non-uniform driver response is diaphragm resonance. These resonances are also the major energy storage mechanism.

In the case of the CS3.6 tweeter, a metal diaphragm is used that is stiff and light enough so the lowest diaphragm resonance occurs above the range of hearing at 26 KHz. Therefore, there are no resonances in the audible range to cause energy storage or response irregularities.

The CS3.6 mid driver uses a very effective new method of greatly reducing diaphragm resonance (patent applied). The diaphragm is constructed of two cones, each with a different shape, which are joined at the rim and at the neck with only air between them. The resulting three-dimensional structure is drastically stronger than a conventional diaphragm of equal weight. This increased strength causes the frequency of lowest diaphragm resonance to be substantially higher and low level vibrations to be substantially less.

Figure 1 illustrates a conventional diaphragm and the vibrations that normally cause irregular frequency response. **Figure 2** shows the response of a CS3.6 mid driver built with a conventional diaphragm. Apparent in the response is a depression in the 1 to 2 KHz region followed by a hump from 2 to 3 KHz, a dip at 4 KHz and a final peak at 4.7 KHz. These irregularities are due to diaphragm resonances. **Figure 3** is the frequency response of this driver through time and illustrates how the resonances cause the driver's output to ring. It can be seen that the driver's output up to 5 KHz requires 1 milli-second (ms) before reducing to the -20 dB floor.

Figure 4 illustrates the new diaphragm. **Figure 5** shows that the response is much more uniform than the conventional driver and shows far fewer irregularities. **Figure 6** shows that diaphragm resonances are virtually eliminated below 7 KHz. Even the one resonance at 7 KHz is mild. Below 6 KHz the driver's output is exceptionally clean, reaching the -20 dB floor in less than 0.5 ms.

The CS3.6's woofer is the first in a THIEL product to employ a metal diaphragm. The anodized aluminum material provides much higher stiffness and compressive strength than conventional diaphragm materials. The primary

Figure 1 Conventional diaphragm with vibration

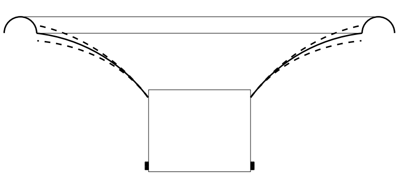


Figure 2 Frequency response of conventional diaphragm

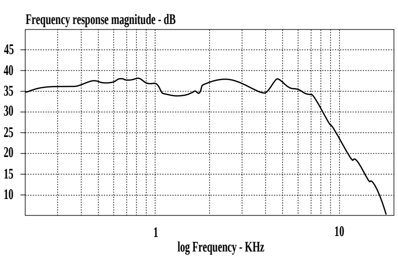


Figure 3 Frequency-time response of conventional diaphragm

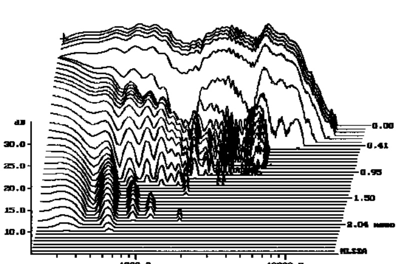


Figure 4 New double diaphragm

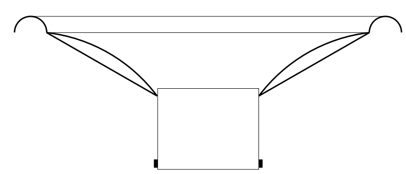


Figure 5 Frequency response of new diaphragm

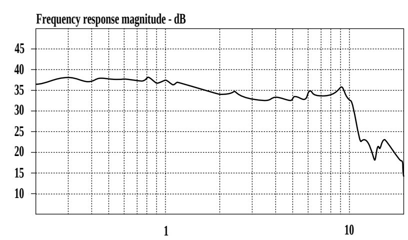
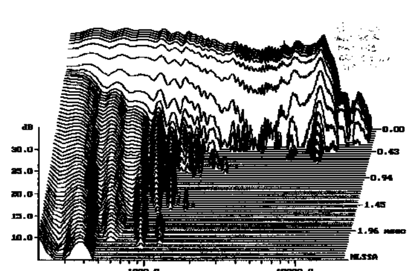


Figure 6 Frequency-time response of new diaphragm



benefit provided is that the lowest resonance is at 2 KHz, two octaves above the crossover frequency. Below 2 KHz there are no resonances to store energy and cause ringing. An additional benefit is that the aluminum's much higher compressive strength results in almost all the energy of a transient attack being transferred to sonic output rather than being absorbed in compression of the diaphragm material.

Even though the diaphragm resonance at 2 KHz is two octaves above the crossover, it's ringing would cause a slight sonic effect if not corrected. We have therefore incorporated into the electrical network a notch filter which complements and cancels the resonance. To our knowledge, this is the first application of a metal woofer with resonance compensation. **Figure 7** shows the time response of the woofer with its crossover network but without resonance compensation. The peak with its consequent ringing at 2 KHz can be clearly identified. **Figure 8** shows the time response with resonance compensation. Although some trace of the resonance is still discernible, it has been drastically reduced to a minor level.

Figure 7 Time response of woofer without compensation

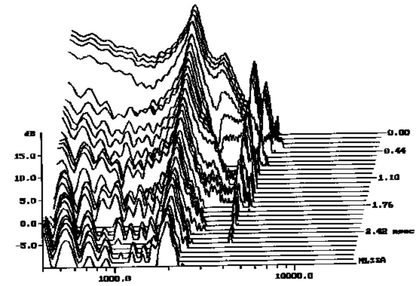
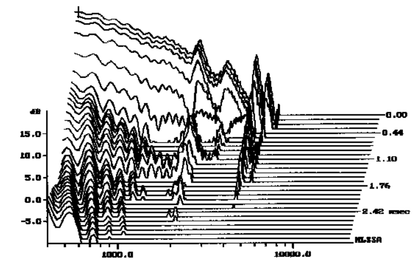


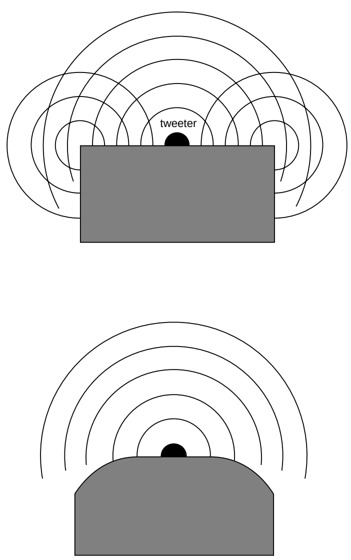
Figure 8 Time response of woofer with compensation



Diffraction

Diffraction causes frequency response and time response errors and therefore a reduction in tonal, spatial, and transient fidelity. Diffraction occurs when some of the energy radiated by the drivers is re-radiated from the cabinet edges at a later time. For musical signals that remain constant for a few milli-seconds, diffraction causes, by constructive and destructive interference, an excess of energy to the listener at some frequencies and a deficient amount of energy to the listener at other frequencies. Diffraction also causes all transient signals to be radiated to the listener a second (and possibly a third) time, smearing transient impact and distorting spatial cues.

Cabinet-edge diffraction



To greatly reduce diffraction the CS3.6 employs a front baffle that is curved at the edges so energy radiated along the baffle can continue into the room without encountering abrupt cabinet edges. **Figures 9** and **10** illustrate the beneficial effects of the CS3.6's curved baffle on the response of the tweeter.

Figure 9 Response of tweeter in square-edged cabinet

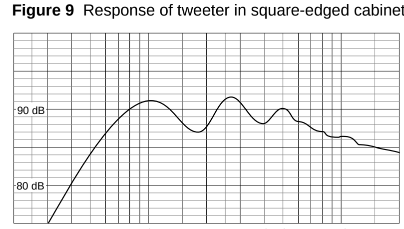
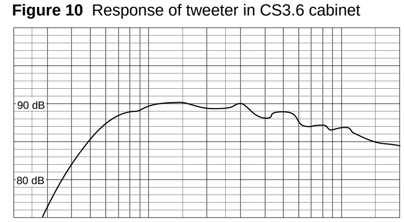


Figure 10 Response of tweeter in CS3.6 cabinet



Results

The end result of greatly reducing diffraction and diaphragm resonances is a speaker with very accurate tonal characteristics. **Figure 11** shows the on-axis frequency response of the CS3.6. It is uniform within ±1.5 dB from 28 Hz to 20 KHz. Typically, it is within ±1 dB from 30 Hz to 10 KHz. Subjectively even more important is the octave-averaged frequency response. **Figure 12** shows this response to be within ±0.5 dB from 36 Hz to 20 KHz showing extremely accurate overall tonal balance. Furthermore, as a result of gradual crossover slopes and relatively low crossover points made practical by the use of high output driver design, the off-axis frequency response of the speaker system is almost as smooth as its on-axis response. This unusual performance is important for producing a uniform amount of ambient energy at all frequencies, necessary for natural spatial reproduction. **Figure 13** shows this octave-averaged, 30° off-axis response to be almost within ±1 dB from 33 Hz to 17 KHz, showing extremely uniform dispersion of energy at all frequencies.

Figure 11 On-axis frequency response

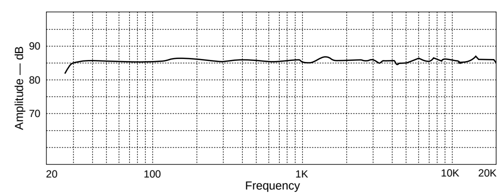


Figure 12 Octave-averaged on-axis frequency response

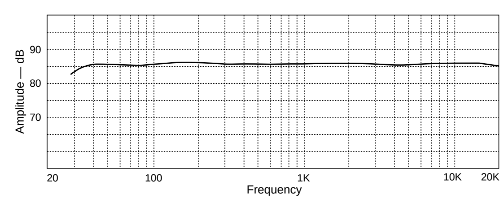
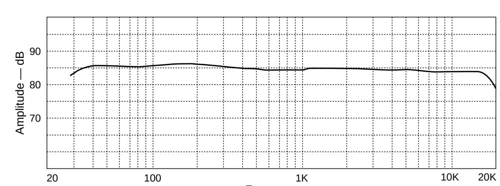


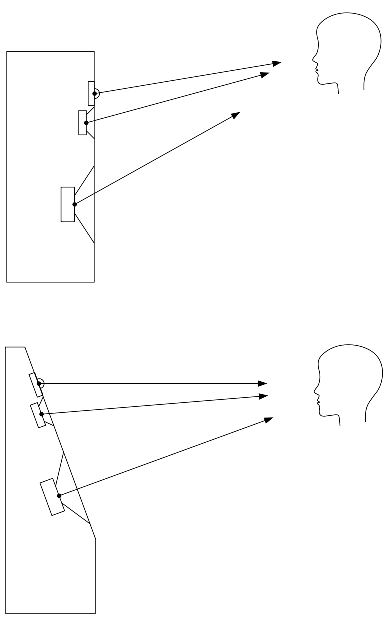
Figure 13 Octave-averaged 30° off-axis frequency response



TIME RESPONSE

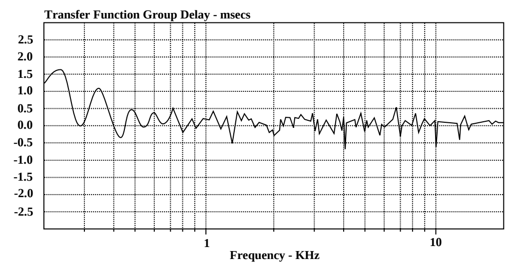
In most loudspeakers the sound from each driver reaches the listener at different times causing the loss of much spatial information. Therefore, with most speakers the only dependable locational clue is the relative loudness of each speaker which causes the sound stage to exist only between the speakers. In contrast to this loudness type of imaging information, the ear–brain interprets real life sounds by using *timing* information to locate the position of a sound. The ear perceives a natural sound as coming from the left mainly because the left ear hears it first. That it may also sound louder to the left ear is of secondary importance.

Time correction



For realistic reproduction, it is important that the attack, or start, of every sound be clearly focused in time. Because more than one driver is involved in the reproduction of the several harmonics of any single sound, the drivers must be heard in unison to preserve the structure of the sound. Since, in most speakers, the tweeter is closer to the listener's ear, the initial attack of the upper harmonics arrives as much as two milliseconds before the body of the sound. This delay results in a noticeable reduction in the realism of the reproduced sound.

Figure 14 Time response



To eliminate this problem the CS3.6 mounts the drivers on a sloped baffle to position them so the sound from each reaches the listener at the same time. This arrangement can work perfectly for only one listening position. However, because the drivers are positioned in a vertical line the error introduced by a listener to the side of the speaker is very small. Also, because the driver spacing is small compared to the wavelength at the crossover frequency, the error introduced by changes in listener height are small within the range of normal seated listening heights provided the listener is 8 feet or more from the speakers.

Figure 14 shows the group delay, the measure of time error, of the CS3.6 from 200 Hz to 20 KHz. For all frequencies above 300 Hz the delay is less than 0.5 ms. The general trend is toward zero delay at higher frequencies.

PHASE RESPONSE

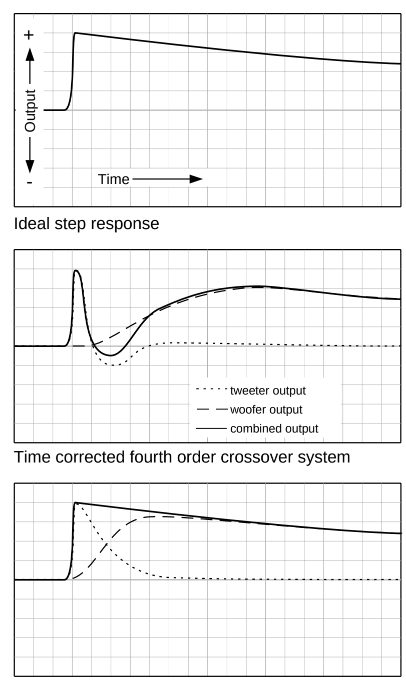
We use the trade mark *Coherent Source* to describe the unusual technical performance of our products. This phrase is descriptive of the time *and* phase coherence which gives THIEL products the unusual ability to accurately reproduce musical waveforms.

Usually, phase shifts are introduced by the crossover slopes, which changes the musical waveform and results in the loss of spatial and transient information. During the past decade the fourth order Linkwitz-Riley crossover has risen in popularity and it is sometimes promoted as being phase coherent. What is actually meant is that the two drivers are in phase with *each other* through the crossover region. However, neither driver is in phase with the input signal nor with the drivers' output at other frequencies; there is a complete 360° phase rotation at each crossover point.

There is a type of crossover system that does not introduce any phase shift or time smear, although it is difficult and expensive to execute. This crossover is the first order (6dB/octave) system that THIEL has employed since 1978 in all our *Coherent Source* systems. A first order system is the only type that can achieve perfect phase coherence, no time smear, uniform frequency response, and uniform power response.

A first order system achieves its perfect results by keeping the phase shift of each roll-off to less than 90° so that it can be canceled by the roll-off of the other driver that has an identical phase shift in the opposite direction. The phase shift is kept low by using very gradual (6dB/octave) roll-off slopes which produce a phase lag of 45° for the low frequency driver and a phase lead of 45° for the high frequency driver at the crossover point. Because the phase shift of each driver is much less than 90° and is equal and opposite, their outputs combine to produce a system output with no phase shift and perfect transient response.

Figure 15



Ideal step response

Time corrected fourth order crossover system

First order crossover system

Figure 15 graphically demonstrates how the outputs of each driver in a two-way speaker system combine to produce the system's output. The first graph shows the ideal output. The second shows the operation of a time-corrected, fourth order crossover system. The two drivers produce their output in the same polarity and both drivers start responding at the same time. However, since the high-slope network produces a large amount of phase shift, the tweeter's output falls quickly and the woofer's output increases only gradually. Therefore, the two outputs do not combine to produce the input step signal well but instead greatly alter the waveform.

The third graph shows how, in a first order crossover system, the outputs of the two drivers combine to reproduce the input waveform without alteration.

In practice the proper execution of a first order system requires very high quality, wide bandwidth drivers and that the impedance and response variations of the drivers and the cabinet be compensated across a wide range of frequencies. This task is complex since the *acoustic* outputs of the drivers must roll off at 6 dB/octave and not simply for the networks themselves to roll off at 6 dB/octave. For example, if a typical tweeter with a low frequency roll-off of 12 dB/octave is combined with a 6 dB/octave network, the resulting acoustical output will roll off at 18 dB/octave.

Figure 16 is a plot of the absolute phase response of the CS3.6. It shows that the phase response is within ±20° above 200 Hz and within ±10° from 400 Hz to 15 KHz. However, in our opinion, what is most important is the phase deviation from the mathematical "minimum" phase response of an ideal transducer with the same frequency response. This deviation is called the *excess* phase and is plotted for the CS3.6 in **Figure 17**. This graph shows the excess phase to be less than ±5° to beyond 10 KHz.

The result of phase coherence (in conjunction with time coherence) is that all waveforms will be reproduced without major alterations. The speaker's reproduction of a step waveform best demonstrates this fact. Like musical waveforms, a step is made up of many frequencies which have precise amplitude and phase relationships. For a step signal to be accurately reproduced, phase, time and amplitude response must all be accurate. Because this waveform is so valuable, it is commonly used to evaluate the performance of electronic components. It is not typically used for speaker evaluation because most speakers are not able to reproduce it recognizably. **Figure 18** shows the CS3.6's response to a step. That the step is reproduced so recognizably is the result of accurate phase, time and amplitude response.

Figure 16 CS3.6 phase response

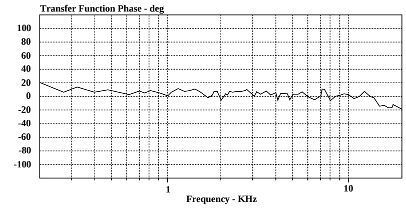


Figure 17 CS3.6 excess phase

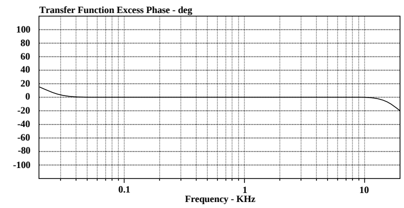
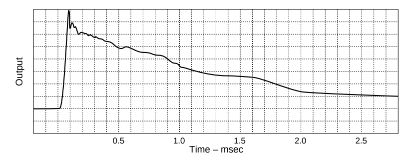


Figure 18 CS3.6 step response



ENERGY STORAGE

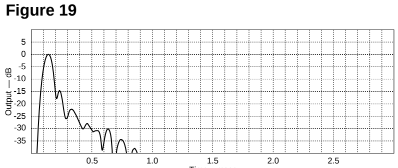
Any part of the speaker that absorbs energy will re-radiate it later in time in a highly distorted manner. Although not loud enough to be consciously heard, stored energy causes significant detrimental effects. The music's subtle detail is obscured, causing both a reduction in clarity and loss of spatiality as well as noticeable colorations of voice and other midrange sounds. The main storage mechanisms are the driver diaphragms and cabinet walls, especially the baffle.

The lack of cabinet wall vibrations is one advantage of membrane speakers and why they have an "unboxy" sound. However the problem of cabinet vibrations in dynamic loudspeakers is not inherent but rather can be reduced as much as is affordable.

One method of attempting to reduce the problem of stored energy is to apply damping to the offending component. The idea is to damp motion with a viscous material so that the stored energy can be dissipated as heat instead of mechanical vibration which produces unwanted sound. This method has limited benefit for two reasons. First, energy can only be dissipated as heat after there is unwanted mechanical vibration to convert. Secondly, even though some of the absorbed energy is transformed into heat, it is still absorbed from the desired sonic output and therefore the distortion mechanism still exists. A much better approach, in our opinion, is to reduce the energy absorbed.

The primary cabinet problem is baffle vibration because movement of the drivers can directly excite the baffle and the resulting extraneous energy it is radiated directly toward the listener. The CS3.6 employs a 3" thick baffle in order to reduce unwanted vibration. The walls of the CS3.6 enclosure are constructed of 1" thick fiberboard, and extensive internal bracing further increases wall stiffness.

Figure 19



To increase the mechanical rigidity and therefore reduce unwanted vibration, all CS3.6 drivers incorporate chassis of cast magnesium rather than stamped steel or plastic.

As previously discussed, much attention has been given to the reduction of diaphragm vibrations to reduce the amount of energy absorbed through resonances.

Figure 19 is the Energy-Time curve of the CS3.6. It shows how the output energy of the speaker is distributed in time. First, it shows that all of the primary energy is focused in the first 150 microseconds, a result of very good time coherence. It also shows that the speaker's output has already decayed to -20 dB after only 200 microseconds and has fallen to -40 dB after only 900 microseconds. This rapid decay provides very clean reproduction with very good inter-transient silence.

DISTORTION

The primary sources of distortion are the drivers' magnetic motor systems and the electrical components of the crossover network. We have taken unusual steps in the design of the CS3.6 to greatly reduce these sources.

Crossover Components

The usual type of capacitor for speakers is electrolytic. This type has the advantage of very low cost but also causes audible distortion due to dielectric absorption and other mechanisms. There are only three electrolytics used in the CS3.6 and none of these is in the signal path. All are used in zobel networks to correct the drivers' impedance and are bypassed with high quality polystyrene types to provide performance closer to the polystyrene type than the electrolytic. The polystyrene capacitors are custom–made to our specifications and employ tin foil rather than aluminum. The use of tin allows the copper lead wires to be soldered, rather than welded, to the conductor resulting in purer sound. The tweeter feed capacitors are pure polystyrene and all other capacitors, including a very large 200 µfd mid-range feed, are polypropylene bypassed with polystyrene.

All the CS3.6 inductors are air-core, which completely eliminates distortions caused by magnetic saturation, and hysteresis and are wound of high purity, low oxygen copper. Also, the speaker's internal wiring uses custom–made solid conductor, high purity copper with polypropylene insulation.

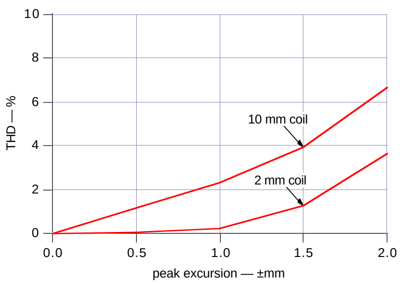
Driver Motor Systems

Unlike the other sources of distortion, motor system distortion is very dependent on volume level, being low during quiet playback levels but increasing rapidly as volume levels increase. At moderate to loud playback levels it is the major source of distortion and can therefore be considered a dynamic range limit. The CS3.6 incorporates several unusual features in its drivers to decrease distortion and increase dynamic range.

Excursion: The most basic limit to dynamic range of a dynamic driver is the limit on diaphragm movement caused by the driving voice coil leaving the magnetic gap beyond a certain excursion. The solution of using a longer coil requires that the magnet be much larger and is therefore usually avoided. The CS3.6 woofer has a very long coil, 13 mm longer than the magnetic gap, which provides output twice as high as typical "long excursion" woofers.

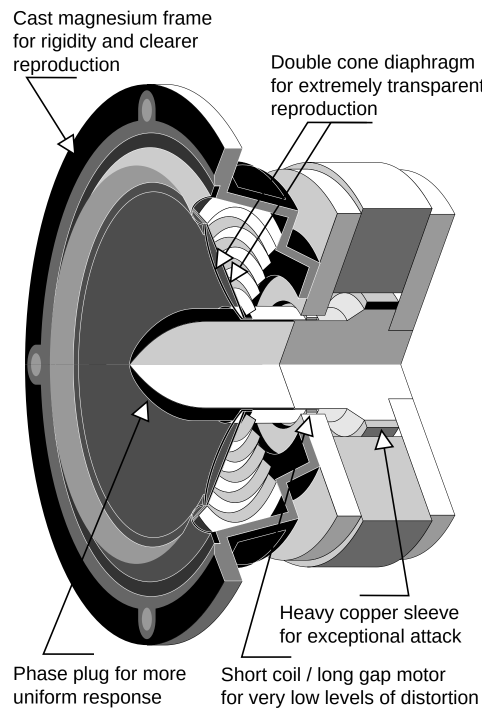
The midrange driver uses a short coil/long gap design that provides very low levels of distortion. As shown in **Figure 20**, the distortion produced by the short coil motor system at normal excursion levels (±1 mm or less) is only one-tenth that produced by the typical long coil system.

Figure 20 Distortion comparison



The tweeter has been specially designed to achieve a dynamic range 15 dB greater than standard tweeters. This performance is achieved by utilizing an unusual wide roll surround and a short coil/long gap magnetic system which allows much greater linear excursion (±1.5 mm).

CS3.6 midrange



Woofer magnet system: The purpose of the driver's motor system is to apply a force to the diaphragm that is directly proportional to the voltage supplied by the amplifier as modified by the electrical network. In order for the force to be directly proportional to the voltage applied, as desired, the magnetic field must be constant, the length of voice coil wire acted on by the magnetic field must be constant, and the current must be directly proportional to the applied voltage. In fact, none of these conditions actually exist but the CS3.6 woofer incorporates refinements of design that improve the accuracy of each of these factors.

The strength of the magnet's field is not actually constant in operation but is changed by the current from the amplifier through the coil. This change occurs because the amplifier current through the coil creates its own magnetic field that "pushes" *against* the magnet's field, generating the force to move the diaphragm. Magnets are somewhat demagnetized by the coil's magnetic field when current flows in one direction and are remagnetized when current flows in the opposite direction. Therefore, since the magnet's field strength is not constant, the force generated is not in the desired direct proportion to the current in the coil. To drastically reduce this effect the CS3.6 woofer incorporates heavy copper rings around the center pole. With these rings any changes in the magnet's strength induces an electrical current in the rings which generates a magnetic field that is opposed to and practically cancels the original change.

A second problem is that the field strength is not symmetrical in front of and behind the gap but is stronger behind the gap than in front of the gap. Therefore, when the diaphragm moves outward, the coil experiences less magnetic field than when it moves inward. This mechanism is the major cause of even harmonic distortion . The woofer in the CS3.6 utilizes a specially shaped pole piece to reduce this problem. **Figure 21** and **figure 22** show the standard and improved field strength symmetry and distortion. At most output levels distortion is reduced by 75%.

The third problem stems from the fact that the coil current is dependent not only on the driving voltage and the coil resistance but also on the coil inductance. The problem is that the coil inductance varies with the amount of iron inside the coil and, with conventional pole piece geometry, changes during the excursions necessary to reproduce low frequencies. As the diaphragm and coil move back, more of the coil is around the pole, increasing the inductance and decreasing the output of the driver by about 1 dB. As the coil moves forward, less of the coil is around the pole, the inductance decreases and the response increases approximately 1 dB. By this mechanism the *frequency response* of the speaker is modulated by driver excursion. This problem has been drastically reduced in the CS3.6 woofer. The same pole geometry which makes the field symmetrical also results in a constant amount of iron inside the coil regardless of coil position. In addition, the problem is further reduced by the copper rings around the pole which reduce the inductance of the coil to a small fraction of its normal value by acting as a shorted turn of a transformer secondary winding.

Figure 21 Field strength and distortion of standard pole geometry

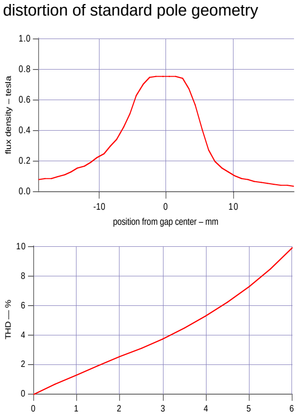
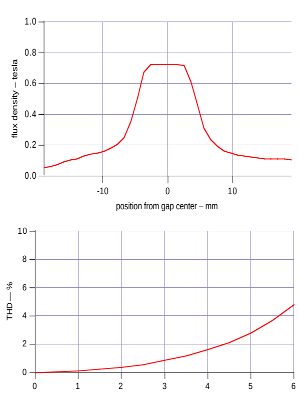


Figure 22 Field strength and distortion of CS3.6 woofer



All of these design details contribute to the CS3.6's exceptional technical performance, its accurate reproduction of all musical information, and its ability to faithfully reproduce the musical experience.