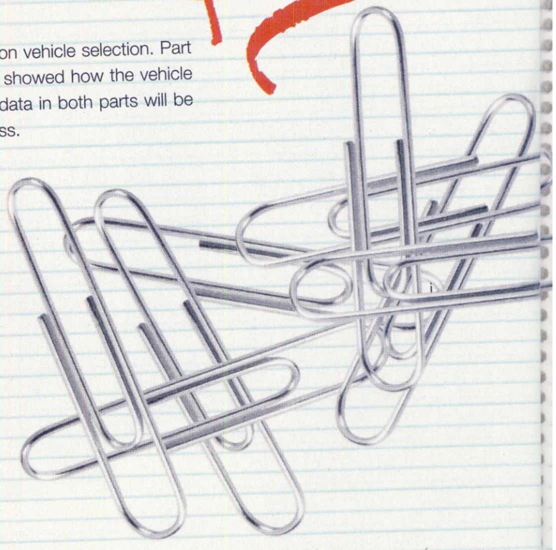
The Car Audio System Nobody Would Build part 3

CAREFUL CONSIDERATION BEFORE CHOOSING YOUR COMPONENTS

BY JON R. WHITLEDGE

Part one in this series discussed my system performance goals and their influence on vehicle selection. Part two examined the acoustics of the vehicle, both theoretically and experimentally, and showed how the vehicle was treated with damping and barrier materials. The system performance goals and data in both parts will be used in this article to define the system configuration and aid in the component selection process.



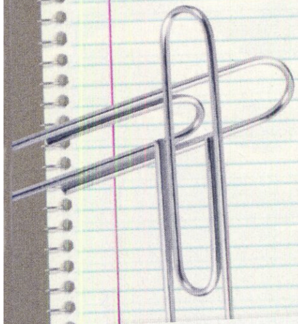
Channels and Crossovers

IASCA's competition CD contains musical information in a 2-channel stereo format. Fortunately, this is the format I believe best reproduces music. In part one, it was established that the audio system would consist of tweeters, midranges, and woofers the front soundstage, and a subwoofer system located in the rear of the vehicle. Therefore, the design would be a 4-way, 2-channel stereo system.

Although the use of passive crossovers is quite common, I wished to use active crossovers and quad-amplification. Vance Dickason says there are many reasons why active crossovers are advantageous, including lower inter-modulation distortion, increased dynamic range, improved transient performance, better coupling between the amplifier and the speaker, avoidance of passive crossover–induced tweeter resonances, better crossover performance working into a constant impedance load, better subjective sound quality than high-level networks, easier control over driver sensitivity differences, and easier manipulation of phase, time delay, and equalization.[1]

Source and Processing

When I was designing my system in 2004-2005 only a few audiophile-grade head units capable of meeting my specifications existed. Of these, I believed the head unit and processor from Alpine's F#1 Status product line were the best choice. Specifically, I chose Alpine's DVI-9990 DVD audio/video tuner and PXI-H990 multimedia manager. These extraordinary components communicate with one another using two, noise-immune digital cables. One of the cables is Alpine's proprietary IONBUS cable, and the second is Alpine's DVD Audio Link cable. The use of the DVD Audio Link cable permitted the digital information from the head unit to remain in the digital domain prior to digital signal processing (DSP).



The digital cables were 6 meters (19.69 feet) long, which would permit the PXI-H990 to be mounted on the overhead electronics console in close proximity to the amplifiers. The PXI-H990 was equipped with eight analog outputs, six of which would be used for the front soundstage, and two of which would be used for the subwoofer. With this layout, the interconnects for the front soundstage could be as short as possible, typically between 0.25 (9.84 inches) and 1.5 meters (59.06 inches). The interconnects for the subwoofer, however, would be necessarily long at about 6 meters. Creating the best possible front soundstage was one of my design goals, so I believed this configuration was ideal.

Alpine's PXI-H990 would be set to the "SYSTEM2" configuration, which would provide eight channels of analog output, one each for the front left tweeter, front right tweeter, front left midrange, front right midrange, front left woofer, front right woofer, subwoofer one, and subwoofer two. Since my goal was to play music in the 2-channel stereo format, the "PCM STEREO" output mode would be chosen. Each of the analog outputs could be fully programmed in the digital domain using the operator interface in the DVI-9990. Parameters including level (± 9dB), crossover frequency, lowpass and highpass crossover slopes (6, 12, 18, 24, or 30 dB/octave), phase (0 or 180 degrees), and time delay (± 50 microsecond resolution) were available for each of the eight channels. In addition, 31 bands of equalization were available for each of the left and right channels as well as 10 bands of equalization for each of the two subwoofer channels. Parametric equalization was also available as an alternative to the "Graphic EQ," but this feature precluded the use of the Graphic EQ and couldn't be used in conjunction with the Graphic EQ.

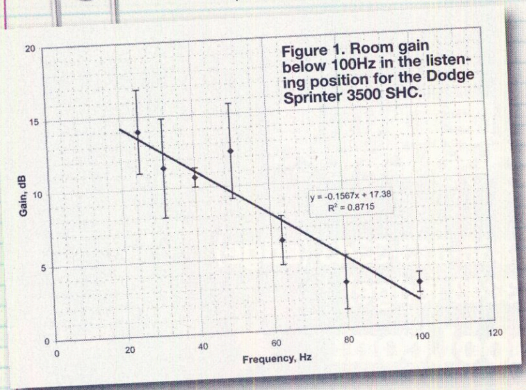


Figure 1. Room gain below 100Hz in the listening position for the Dodge Sprinter 3500 SHC.

Power and Sound Quality

In part one, I provided a family of un-weighted sound pressure level (SPL) curves incorporating B-weighted compensation to be used as a guideline for selecting the appropriate amplifier power for the loudspeaker systems. The curves established that significant levels of power are required for an audio system dedicated to sound quality, especially at the extremes of the frequency range, particularly for the 90- and 100-phon curves. Although I believed a system dedicated to sound quality should be designed along the 70- or 80-phon curves, I desired to build a system where each loudspeaker transducer was powered by its own amplifier channel (preferably a "monoblock") with the maximum possible power. I believed by directly driving each loudspeaker transducer with maximum power and control, the highest sound quality would be achieved.

Enclosure Type

Among the many decisions related to system design, one involved the choice of loudspeaker enclosure type. Based on my research, I believed sealed, as opposed to ported, enclosures provided superior performance for many reasons. Most importantly, the low frequency roll-off of sealed enclosures is 12dB/octave unlike ported enclosures, which roll-off at 24dB/octave. Although a ported enclosure can be designed with a lower cutoff point, Robert Harley, editor of *The Absolute Sound* magazine, says, "Subjectively, a higher cutoff frequency with a more gradual roll-off provides a more satisfying feeling of bass fullness than a lower cutoff frequency and steeper roll-off." Harley continues, "A sealed enclosure will generally have much better transient response and better bass definition, at the cost of lower sensitivity and less deep bass extension."[2]

In addition, it's known that ported enclosures are prone to port resonances, and suffer from increased group delay.[3] Fortunately, the low-frequency roll-off of the drivers is counteracted, to some extent, by room gain. In part two, the room gain was determined experimentally and shown to be significant below about 100Hz. In order to employ room gain in the calculations of amplifier power requirements, I re-plotted the room gain below 100Hz and fitted the data with an appropriate function, as shown in **Figure 1**. The data was best fitted by a linear function, since the correlation coefficient ($R2 = 0.8715$) was reasonable and the best fit line was essentially within the uncertainty bars.

Given the established design input requirements, loudspeakers were selected and modeled using their Thiele-Small parameters and power handling capabilities in a simple spreadsheet designed to estimate sealed box performance characteristics.[4] For each loudspeaker system calculation, an appropriate choice of system Q was made and the resulting enclosure volume, resonant frequency, and maximum thermally- or displacement-limited output as a function of frequency was determined. For two drivers playing uncorrelated information, the outputs were increased by 3dB.[5] For two or three drivers playing correlated information, the outputs were increased by 6 or 9.54dB, respectively.[6] Finally, room gain, determined from the linear equation, was added to the result to estimate the total output of the loudspeaker system.

Selecting Appropriate Speakers

The next decision in the system design and configuration process involved the choice of loudspeaker transducers. My former award-winning competition vehicle used Dynaudio's loudspeaker transducers, and they performed flawlessly for more than three years. As a polymer scientist and mechanical engineer, I appreciate the obvious build quality of their mobile audio loudspeaker transducers. More importantly, as an audiophile and mobile audio competitor, their sound quality allows me to create extraordinarily lifelike mobile audio systems.

From Dynaudio's product line, I selected the MD130 tweeters. Based on the legendary Esotar D-260 soft-dome tweeter used in home audio applications, but redesigned for mobile applications, I believed they provided the optimum balance between mounting depth and power handling. I especially liked how the male speaker terminals were configured, since one could attach female speaker terminals in a compact manner whereby the speaker wire and connections wouldn't protrude beyond the rear of the body of the tweeter. According to Dynaudio's literature, the MD130 will handle 130 watts of continuous power; therefore, the output of two MD130 tweeters was predicted to be about 111dB.[7] This result indicated the MD130 tweeters were capable of output along the 100-phon loudness curve, and more than satisfied my design requirements. Dynaudio's literature states the resonant frequency of the MD130

Sealed Enclosure calculations	v1.11				
Driver Specifications					
Driver	Dynaudio MW150				
Vas	4.500	litres	Equivalent air compliance	0.159	cu.ft.
Qts	0.520		Total driver Q at resonance		
Qes	0.680		Driver electrical Q at resonance		
fs	70.0	Hz	Driver resonance frequency		
Xmax	6.00	mm	Maximum linear excursion	0.24	in.
Dia.	10.50	cm	Effective diameter	4.13	in.
PEMax	100	watts	Thermal power rating		
Constants					
Ro	1.18	kg/m^3	Density of air at room temperature		
c	345.00	m/s	Speed of sound in air		
Enclosure Specifications					
Desired Qtc	0.71		Total system Q at resonance		
Qr	1.36				
Vr	0.85				
Vb	5.30	litres	Net box size	0.19	cu.ft.
Fb	95.2	Hz	System resonance frequency		
F3	95.2	Hz	Cutoff frequency (-3dB)		
Sd	8.66E-03	m^2	Cone surface area		
Vd	5.20E-05	m^3	Volume displaced by cone at maximum linear excursion		
n0	0.002		Driver efficiency		
SPL	85.4	dB/1W/1m	Driver efficiency (in dB)		
K1	0.094				
K2	101.729				
Amax	1.000				
Par	0.094		Maximum acoustic power output for system		
Per	43	watts	Input power required to produce Par		
PeakSPL	105	dB	Maximum SPL		

Figure 2. Sealed enclosure calculations for MW150.

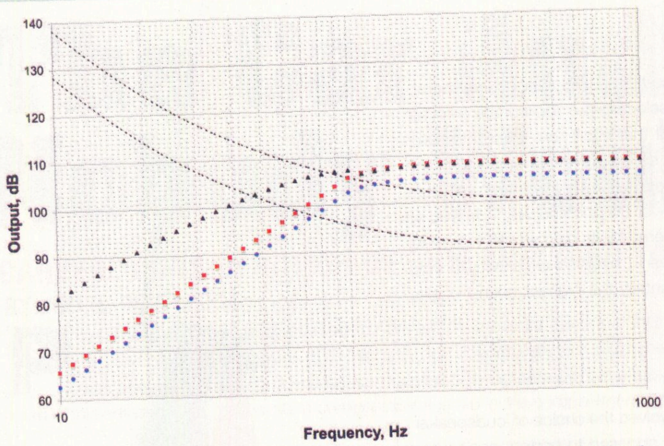
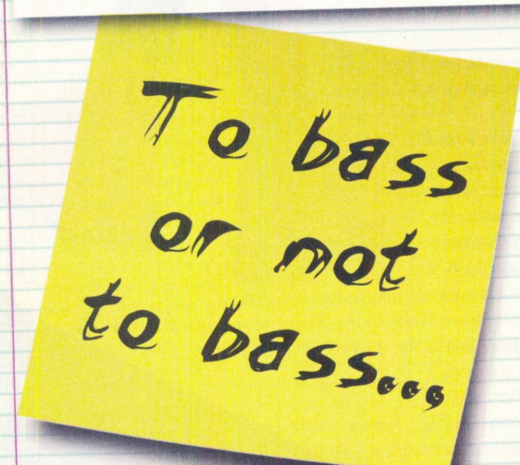


Figure 3. Estimated output of two MW150's. Blue solid circles represent the lesser of the thermally- or displacement-limited output of one MW150. Red solid squares represent the output of two MW150's. Black solid triangles represent the output of two MW150's augmented by room gain. The lower and upper dashed lines represent the 90- and 100-phon curves, respectively.

is 850Hz, which I believed would allow for the use of first-order crossover slopes and the lowest possible crossover frequency, if desired. Furthermore, the front mounting faceplate is removable, if desired, enabling the tweeter to be mounted on a custom faceplate using its inner three-hole bolt circle.[8]

In accordance with my design goals, I selected Dynaudio's MW150 loudspeaker transducers for midrange duties. I chose the MW150's because I believed they would provide the best balance between horizontal polar response, low-frequency extension, and enclosure size. A loudspeaker's horizontal polar response, or radiation pattern, narrows as the frequency increases and, therefore, is the limiting factor for the upper crossover frequency. Using a stringent attenuation limit of -3dB at 45 degrees off-axis, a 4-inch diameter driver can play up to 2,687Hz, while a 5-inch driver can play up to 2,051Hz.[9] I believed the use of Dynaudio's MW150 loudspeaker transducer, as opposed to a larger transducer, would result in better lateral dispersion and superior integration with the tweeter's radiation pattern.



Dynaudio's literature states the MW150 has a resonant frequency of 70Hz and will handle 100 watts of continuous power. Dynaudio recommends an enclosure volume of 5.7-14.2 liters (0.2-0.5ft^3) and suggests the transducer is capable of playing from 55-3,500Hz. Believing that a loudspeaker system Q of 0.707 would provide ideal transient performance, I substituted Dynaudio's published Thiele-Small parameters into a simple spreadsheet designed to estimate its sealed box performance characteristics. The calculations for one MW150 transducer, as shown in **Figure 2**, indicated the desired enclosure volume was 5.31 liters (0.19ft^3), the resonant frequency of the system was 95.2Hz, and the maximum SPL attainable was 105dB. It seemed reasonable that an enclosure, approximately 5.3 liters in volume, containing both the tweeter and the midrange mounted in close proximity to one another, would fit in the vicinity of the A-pillar/dash junction without significantly obstructing the driver's vision of the road or the rearview mirrors.

Figure 3 shows the estimated output of two MW150's augmented by room gain. From the calculations, it appeared that a pair of Dynaudio's MW150 loudspeaker transducers, each powered by 100 watts, essentially met the performance requirements for extremely loud playback levels required along the 100-phon curve down to about 80Hz.

Sealed Enclosure calculations	v1.11				
Driver Specifications					
Driver	Dynaudio MW180				
Vas	61.000	litres	Equivalent air compliance	2.153	cu.ft.
Qts	0.510		Total driver Q at resonance		
Qes	0.620		Driver electrical Q at resonance		
fs	33.0	Hz	Driver resonance frequency		
Xmax	9.00	mm	Maximum linear excursion	0.35	in.
Dia.	17.30	cm	Effective diameter	6.81	in.
PEMax	200	watts	Thermal power rating		
Constants					
Ro	1.18	kg/m^3	Density of air at room temperature		
c	345.00	m/s	Speed of sound in air		
Enclosure Specifications					
Desired Qtc	1.00		Total system Q at resonance		
Qr	1.96				
Vr	2.84				
Vb	21.44	litres	Net box size	0.76	cu.ft.
Fb	64.7	Hz	System resonance frequency		
F3	50.9	Hz	Cutoff frequency (-3dB)		
Sd	2.35E-02	m^2	Cone surface area		
Vd	2.12E-04	m^3	Volume displaced by cone at maximum linear excursion		
n0	0.003		Driver efficiency		
SPL	87.3	dB/1W/1m	Driver efficiency (in dB)		
K1	0.333				
K2	107.222				
Amax	1.155				
Par	0.250		Maximum acoustic power output for system		
Per	73	watts	Input power required to produce Par		
PeakSPL	110	dB	Maximum SPL		

Figure 4. Sealed enclosure calculations for MW180.

In accordance with my design goals, I selected Dynaudio's MW180 loudspeaker transducers for woofer duties. Dynaudio's literature states the MW180 has a resonant frequency of 33Hz and will handle 180 watts of continuous power. The company recommends an enclosure volume of 21.2-56.6 liters (0.75-2ft^3) and suggests the transducer is capable of playing from 30-2,000Hz. Given the woofers would be mounted in the doors, where the enclosure volume was limited, I modeled the woofer system with a Q of 1.0, instead of 0.71, which estimated the smallest feasible enclosure volume. With a system Q of 1.0, I believed the appropriate use of enclosure stuffing would adequately lower the Q to a more optimal value. Dickason, using a 10-inch diameter (254mm) woofer system, demonstrated this was possible, by reducing the system Q from 1.19, in the unfilled condition, to 0.73 in the fully filled condition.[10]

The calculations for one MW180 transducer powered by 200 watts, as shown in **Figure 4**, indicated the minimum acceptable enclosure volume was 21.4 l (0.76ft^3), the resonant frequency of the system was 64.7Hz, and the maximum SPL attainable was 110dB.

That is the question!

Figure 5 shows the estimated output of two MW180's augmented by room gain. From the calculations, it appeared that a pair of Dynaudio's MW180 loudspeaker transducers, each powered by 200 watts, essentially met the performance requirements for extremely loud playback levels required along the 100-phon curve down to almost 40Hz. I intended to fabricate low-profile door enclosures, and the relatively shallow mounting depth of 75mm (2.95 inches) of the MW180 was one of its many favorable attributes. I also believed by properly employing the MW180's in the doors, they would integrate beautifully with the midranges and tweeters, and solidly and coherently anchor the front soundstage.

Harley says, "More often than not, subwoofers degrade a musical system's playback performance. Either the subwoofer is poorly engineered (and many are), or the subwoofer is set up incorrectly." Harley continues, "The subwoofer may move lots of air and provide deep extension, but a poorly executed subwoofer often adds a booming thumpiness to the low end. Rather than increasing our ability to hear what's going on in the bass, a subwoofer often obscures musical information." He adds that a subwoofer may not integrate musically with the main loudspeakers, and that very low frequencies reproduced by the sub can sound different from the midbass from the main speakers. Harley says, "Another factor that can make integrating a subwoofer difficult is matching a slow and heavy subwoofer to taut, lean, and articulate main speakers. Subwoofers often trade tight control, pitch resolution, and lack of overhang for greater sensitivity or deeper extension."[11]

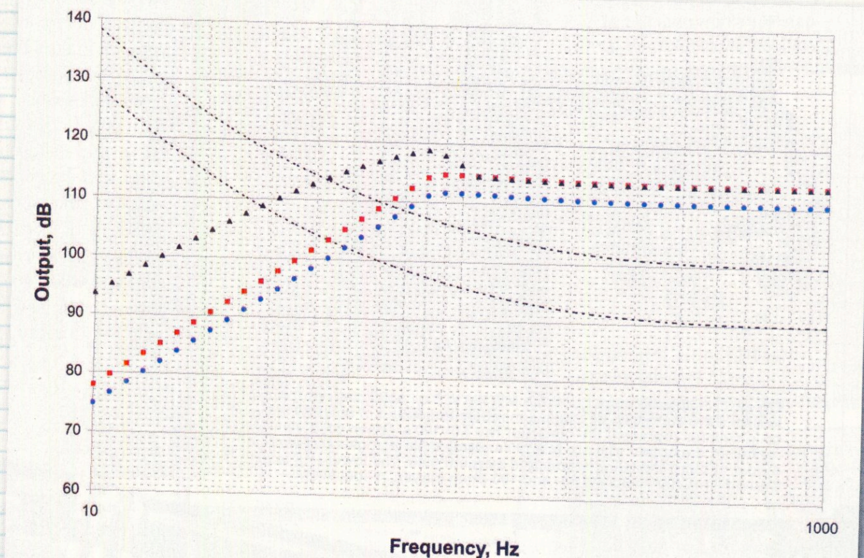


Figure 5. Estimated output of two MW180's. Blue solid circles represent the lesser of the thermally- or displacement-limited output of one MW180. Red solid squares represent the output of two MW180's. Black solid triangles represent the output of two MW180's augmented by room gain. The lower and upper dashed lines represent the 90- and 100-phon curves, respectively.

Steve McCormack, a renowned home audio component designer with over 33 years of critical listening experience, has heard a variety of subwoofer systems throughout his career and pointed out that subwoofers, in general, suffer from integration problems, especially those much larger than a foot (304.8mm) in nominal diameter. Rather than use a large subwoofer from another manufacturer, McCormack recommended that I consider using a plurality of Dynaudio's largest woofer transducers, MW190's, in an isobaric configuration.[12] Dickason says, when two drivers are mounted either back-to-back or face-to-face, and driven electrically out of phase, odd-order non-linearities are cancelled and the result is substantially reduced driver distortion. One of the major advantages of the isobaric design is the enclosure volume is half of that required for a single driver, however, the output is the same as a single driver.[13]

Dynaudio's literature states the MW190 has a resonant frequency of 31Hz and will handle 190 watts of continuous power. Dynaudio recommends an enclosure volume of 56.5-113 liters (2-3.99ft³) and suggests the transducer is capable of playing from 20-800Hz. Believing that a loudspeaker system Q of 0.90 would provide the best performance, I substituted Dynaudio's published Thiele-Small parameters into a simple spreadsheet designed to estimate its sealed box performance characteristics. The calculations for one MW190 transducer, as shown in **Figure 6**, indicated the desired enclosure volume was 76.1 liters (2.69ft³), the resonant frequency of the system was 52.6Hz, and the maximum SPL attainable was 113dB.

Sealed Enclosure calculations	v1.11				
Driver Specifications					
Driver	Dynaudio MW190				
Vas	143.400	litres	Equivalent air compliance	5.062	cu.ft.
Qts	0.530		Total driver Q at resonance		
Qes	0.640		Driver electrical Q at resonance		
fs	31.0	Hz	Driver resonance frequency		
Xmax	9.00	mm	Maximum linear excursion	0.35	in.
Dia.	22.56	cm	Effective diameter	8.88	in.
PEMax	190	watts	Thermal power rating		
Constants					
Ro	1.18	kg/m^3	Density of air at room temperature		
c	345.00	m/s	Speed of sound in air		
Enclosure Specifications					
Desired Qtc	0.90		Total system Q at resonance		
Qr	1.70				
Vr	1.88				
Vb	76.13	litres	Net box size	2.69	cu.ft.
Fb	52.6	Hz	System resonance frequency		
F3	43.7	Hz	Cutoff frequency (-3dB)		
Sd	4.00E-02	m^2	Cone surface area		
Vd	3.60E-04	m^3	Volume displaced by cone at maximum linear excursion		
n0	0.006		Driver efficiency		
SPL	90.1	dB/1W/1m	Driver efficiency (in dB)		
K1	0.422				
K2	108.249				
Amax	1.082				
Par	0.360		Maximum acoustic power output for system		
Per	56	watts	Input power required to produce Par		
PeakSPL	113	dB	Maximum SPL		

Figure 6. Sealed enclosure calculations for MW190.

Figure 7 shows the estimated output of three MW190's augmented by room gain. From the calculations, it appeared that three of Dynaudio's MW190 loudspeaker transducers, each powered by 190 watts, weren't sufficient to play at the required loudness of 124dB at 20Hz along the 100-phon curve, but were easily capable of playing down to 20Hz along the 90-phon curve. Nonetheless, playback along the 90-phon curve exceeded my design output requirements. Of course, for the isobaric implementation, six MW190's would be required. The calculations indicated that 1,140 watts (6 x 190 watts) of power and a total enclosure volume of 114.2 liters (76.13 ÷ 2 x 3) (4.03ft³) would be required.

It's worth noting the effective cone area of three MW190's is essentially equivalent to one transducer with an effective cone diameter of 390.9mm (15.39 inches). This is essentially equivalent to that of a typical commercially available 18-inch diameter subwoofer. Instead of using one heavy cone, the proposed design benefits from the lower moving mass of three lighter cones. I believed the proposed subwoofer design would maximize bass quality and result in exceptional integration with the front soundstage, while at the same time delivering considerable power and bass extension. Furthermore, I believed the use of Dynaudio's MW190 loudspeaker transducers was integral to the success of my subwoofer system. Indeed, many respected audiophiles who have heard my system, say that it possesses the tightest, cleanest, most articulate, deepest, and best integrated bass they've heard in a mobile audio system.

This article stressed the benefits of active crossovers and the importance of room gain and loudspeaker simulations as design inputs to aid in the selection of loudspeaker transducers and determination of amplification power. Stay tuned for part four where I'll continue to discuss my system design goals and further explain the component selection process.

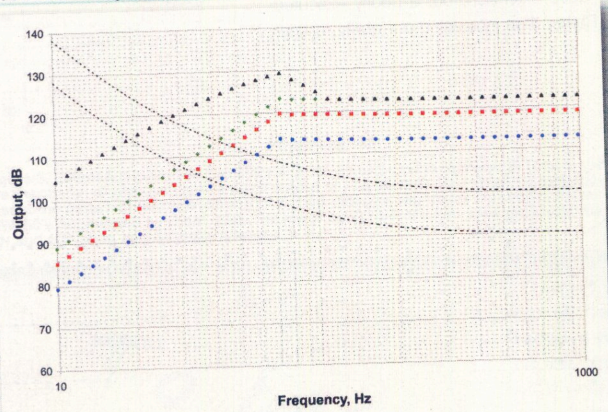
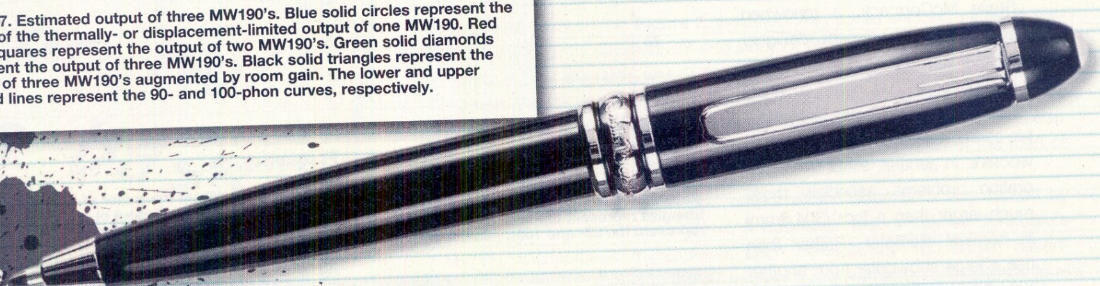


Figure 7. Estimated output of three MW190's. Blue solid circles represent the lesser of the thermally- or displacement-limited output of one MW190. Red solid squares represent the output of two MW190's. Green solid diamonds represent the output of three MW190's. Black solid triangles represent the output of three MW190's augmented by room gain. The lower and upper dashed lines represent the 90- and 100-phon curves, respectively.



Resources

1. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, p. 152, 2000.
2. R. Harley, The Complete Guide to High-end Audio, 1st Ed., Acapella Publishing, pp. 191-192, 1994.
3. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, pp. 55-69, 2000.
4. The DIY-Subwoofer Page, Sealed Systems subcategory, SEALED.XLS freeware, see http://www.diysubwoofers.org/sld/
5. M. Rettinger, Acoustic Design and Noise Control, Chemical Publishing Co. Inc., p. 9, 1973.
6. M. Rettinger, Acoustic Design and Noise Control, Chemical Publishing Co. Inc., pp. 8-9, 1973. For two equal, in-phase sound sources, the following equation applies:

$$P = \sqrt{\left(P_1^2 + P_2^2 + 2P_1P_2\cos(q_1 - q_2)\right)}$$

For in-phase sound sources, the cosine term is zero, and the equation reduces to:

$$P = \sqrt{\left(P_1^2 + P_2^2 + 2P_1P_2\right)} \quad P = \sqrt{(P_1 + P_2)^2} \quad P = P_1 + P_2 \quad P = 2P \quad SPL = 20 \ \log \frac{2P}{P} = 6dB$$

Note that I derived the value of 9.54dB for three equal, in-phase sound sources, using the following equations: Let $P_1 = 2P$ and $P_2 = P$, then

$$P = 2P + P \quad P = 3P \quad SPL = 20 \ \log \frac{3P}{P} = 9.54dB$$

7. From Dynaudio's product literature, the sensitivity of the MD130 is estimated to be 90dB at 1-watt/1-meter at 8 ohms. Hypothetically, when using an amplifier with power ratings derived at 4 ohms (as most car audio amplifiers are), the power will be reduced by half when introduced to an 8-ohm load. Therefore, powered by 128 watts, the loudspeaker transducer would produce a sound pressure level ("SPL") of 108dB. Two transducers producing uncorrelated sound would provide for an additional 3dB of output, bring the total SPL of the tweeters to 111dB.
8. Exercise extreme care if removing the faceplate, as the tweeter can be inadvertently disassembled. In addition, the M4 mounting holes have shallow counter bore depths. If the mounting screws are too long, the tweeter may be damaged; if the screws are too short, the threads may strip. These considerations are the result of an exquisitely designed tweeter assembly, and should not be interpreted as limitations or design flaws.
9. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, p. 105, 2000.
10. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, pp. 34-35, 2000.
11. R. Harley, The Complete Guide to High-end Audio, 1st Ed., Acapella Publishing, pp. 202-204, 1994.
12. Private communication. Visit http://www.smcaudio.com.
13. V. Dickason, The Loudspeaker Design Cookbook, 6th Ed., Audio Amateur Press, p. 43, 2000.