Loudspeaker Driver Characterization

By Bohdan Raczynski - August 2021

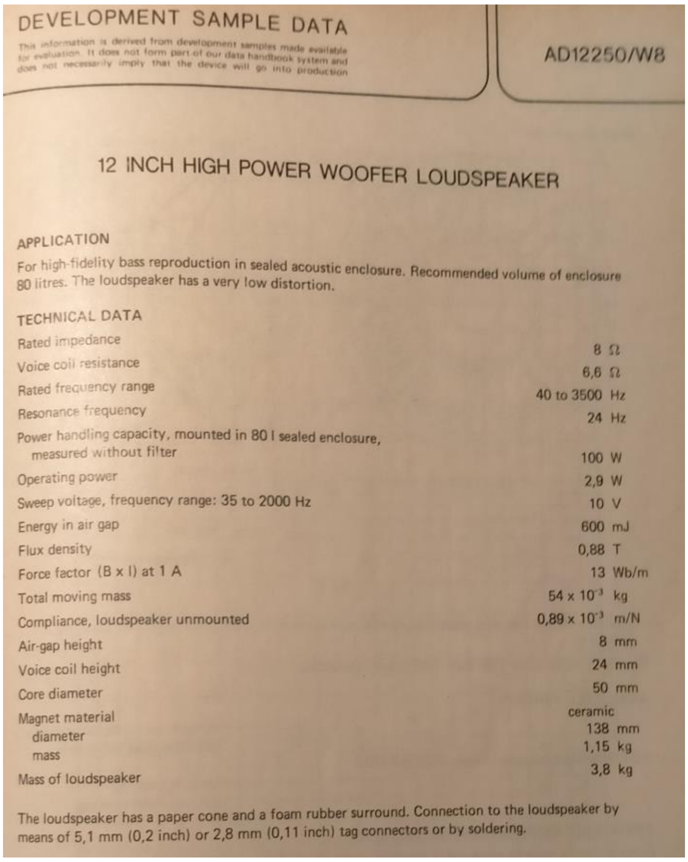
Background

Ideally, loudspeaker driver data associated with any particular driver, would be comprehensive enough to enable the system designer to enter all this information into a CAD program and create at least a “first cut” design of the intended system. If the first cut design passes initial criteria of the expected performance, then the design process becomes validated and established and a new loudspeaker system will hopefully see the light of the day. This would be my approach to loudspeaker design. It’s not the only one, and other methods have been used too. Loudspeaker data bases exist already. But to my knowledge, none of them supports driver “pick-and-place” design freedom.

So, what information would have to be associated with a loudspeaker driver to make it usable across a number of possible trials for the first cut design?.

Where did I start?

Historically, from my personal experience, I think it started with simple electro-mechanical data with of SPL curves measured with drivers in boxes in anechoic chambers. Here is an example of Philips Components And Materials data, Part 3b, from October 1978 – Loudspeakers.



DEVELOPMENT SAMPLE DATA

This information is derived from development samples made available for evaluation. It does not form part of our data handbook system and does not necessarily imply that the device will go into production

AD12250/W8

12 INCH HIGH POWER WOOFER LOUDSPEAKER

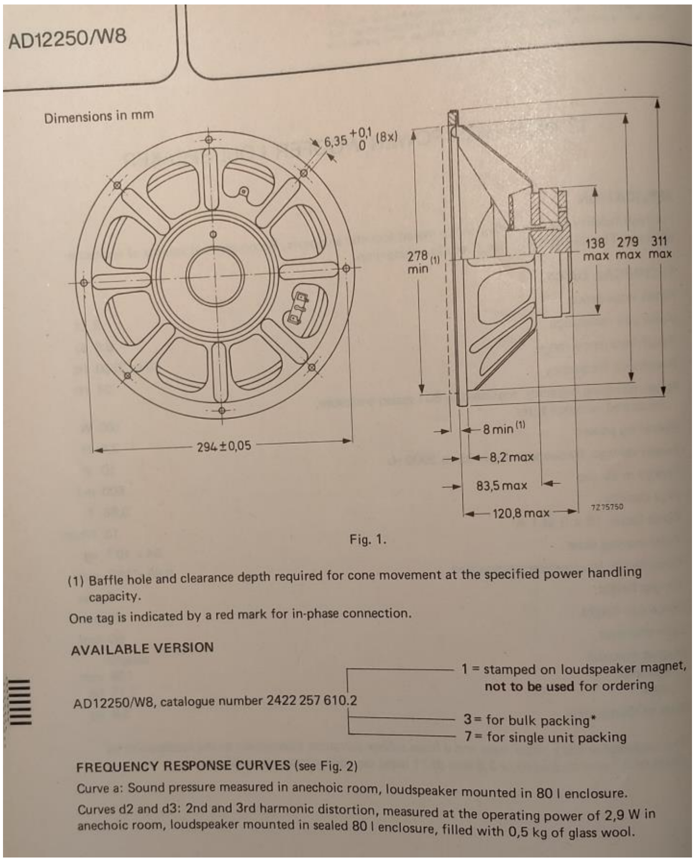
APPLICATION

For high-fidelity bass reproduction in sealed acoustic enclosure. Recommended volume of enclosure 80 litres. The loudspeaker has a very low distortion.

TECHNICAL DATA

Rated impedance	8 Ω
Voice coil resistance	6,6 Ω
Rated frequency range	40 to 3500 Hz
Resonance frequency	24 Hz
Power handling capacity, mounted in 80 l sealed enclosure, measured without filter	100 W
Operating power	2,9 W
Sweep voltage, frequency range: 35 to 2000 Hz	10 V
Energy in air gap	600 mJ
Flux density	0,88 T
Force factor (B x l) at 1 A	13 Wb/m
Total moving mass	54×10^{-3} kg
Compliance, loudspeaker unmounted	$0{,}89 \times 10^{-3}$ m/N
Air-gap height	8 mm
Voice coil height	24 mm
Core diameter	50 mm
Magnet material	ceramic
diameter	138 mm
mass	1,15 kg
Mass of loudspeaker	3,8 kg

The loudspeaker has a paper cone and a foam rubber surround. Connection to the loudspeaker by means of 5,1 mm (0,2 inch) or 2,8 mm (0,11 inch) tag connectors or by soldering.



AD12250/W8

Dimensions in mm

Fig. 1.

(1) Baffle hole and clearance depth required for cone movement at the specified power handling capacity.

One tag is indicated by a red mark for in-phase connection.

AVAILABLE VERSION

AD12250/W8, catalogue number 2422 257 610.2

1 = stamped on loudspeaker magnet, **not to be used** for ordering

3 = for bulk packing*

7 = for single unit packing

FREQUENCY RESPONSE CURVES (see Fig. 2)

Curve a: Sound pressure measured in anechoic room, loudspeaker mounted in 80 l enclosure.

Curves d2 and d3: 2nd and 3rd harmonic distortion, measured at the operating power of 2,9 W in anechoic room, loudspeaker mounted in sealed 80 l enclosure, filled with 0,5 kg of glass wool.

Please note, that “Curve a” on the picture below, is the driver’s SPL curve measured in anechoic chamber, with loudspeaker mounted in 80lt enclosure, filled with 0.5kg of glass wool.

“Operating Power” was the sine wave power required the loudspeaker to operate at 96dB SPL level. It was 2.9 watts in this case.

So far, no mention of Thiele/Small (small-signal) parameters.

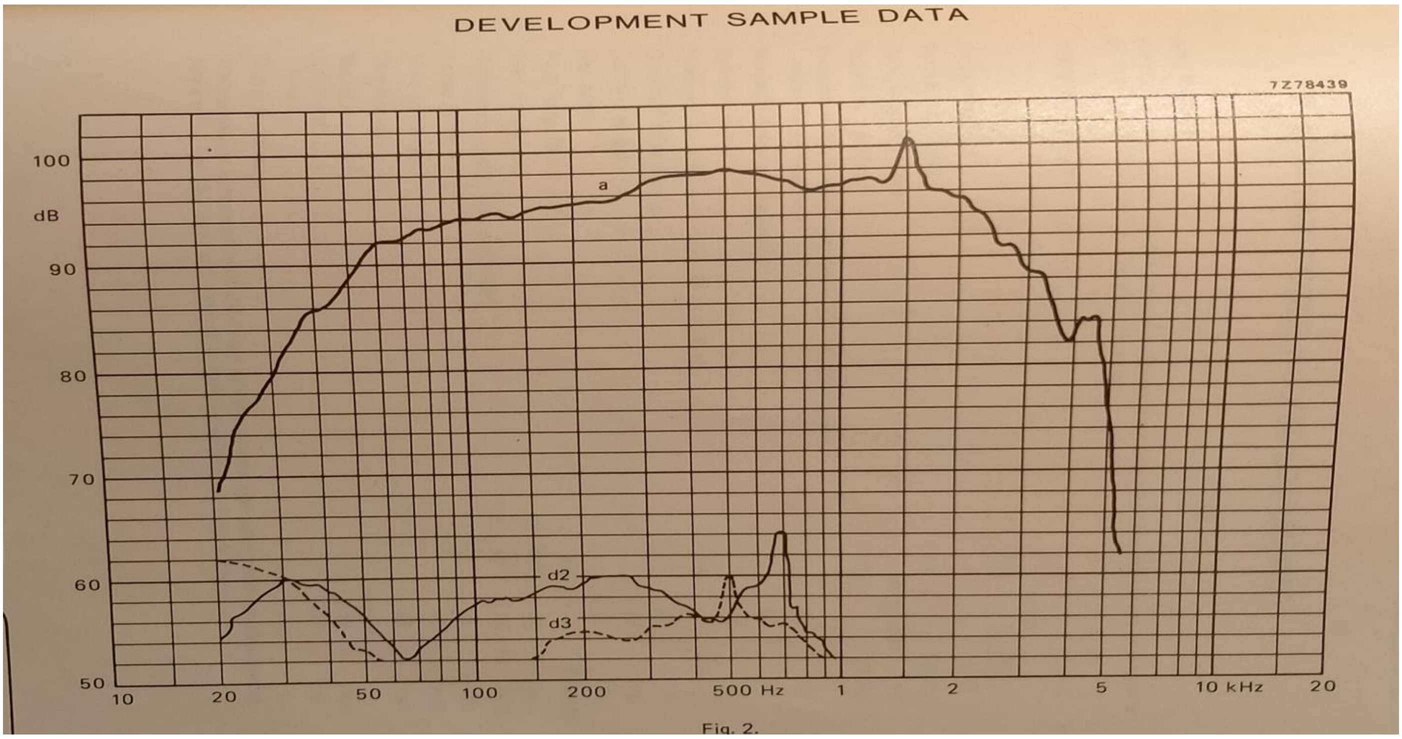


Fig. 2.

Well, that was year 1978, and we have made good progress from those years.

The Thiele/Small (small-signal) parameters were fundamental enablers of the birth of computer CAD programs, which would take T/S parameters and would allow the designer to model driver's behaviour in various enclosures sizes and types.

Next improvement was inclusion of on-axis and off-axis SPL curves and impedance curves data. Voice coils were characterised more accurately, resulting in several models being used for modelling input impedance of a driver.

I could go on…..but this is not the purpose of this paper. Even today, loudspeaker manufacturers do not provide loudspeaker specifications/characterizations – ideally computer data files, which would allow the designer to load the file into the current loudspeaker project and predict (model) the proposed system performance characteristics.

What would it take to change current situation and characterize the loudspeaker driver to a degree, where you could plug-in any driver into the CAD project and predict at least a few basic performance curves: the acoustic on-axis/off-axis SPL/Phase, Zin/Phase, Cone Displacement and limits, and so on?.

What data is needed?

Before listing some basic requirements, we must stress, that the fundamental purpose of the existence of the database is to provide the designer with "minimum cost design path" to achieve the design goal. This requirement translates into model-before-buy principle. So that you would only start investing into the hardware, once you convinced yourself, that the design will fly.

Loudspeaker data collected in its file should allow the following design freedoms and more:

1. Measure the driver's SPL/Phase and Zin/Phase **once only**.
2. Allow for various baffle placements of the driver.
3. Support for unrestricted movement of all drivers on the front baffle.
4. Allow for unlimited variants of system design (2-way….5-way, D'Appollito, arrays, etc…..).
5. Support measurements performed at one distance (e.g.; 1m), but design and optimization executed at different distance (e.g.; 2m).

6. Allow the design of different baffle sizes and shapes.
7. Support different enclosure sizes and types.
8. Support off-axis modelling, even with only on-axis measurement data in the driver file.
9. Provide support data for non-linear analysis of the cone excursion.
10. Provide support for vent performance analysis.
11. Provide SPL/Phase and Zin/Phase data over 750-1000 data point spaced logarithmically from 5Hz-50000Hz.
12. Facilitate linear-phase loudspeaker design.

Regarding Item 1

Just like T/S parameters, loudspeaker driver is uniquely characterised by its SPL/Phase and Zin/Phase performance curves. This data is tied to this particular driver and does not change in the presence or absence of other drivers in the system. Therefore, it makes sense to measure the driver once only and include this data permanently in the driver file. The critical issue here is the universal, standard measurement reference point for SPL/Phase measured data. Since the loudspeaker driver is a minimum-phase device it makes sense to define the “acoustic centre” as the point in space, where the acoustic radiator’s (the driver) transfer function assumes minimum-phase characteristics. Up until now, the stumbling block was the difficulty with accurate extraction of the minimum-phase phase response. The method described in my previous papers removes this problem, so one can accurately extract the minimum-phase and then calculate the acoustic centre (as defined above) from there. As it will be demonstrated later, CAD modelling software should be able to predict all variants of SPL/Phase modelling, when given the SPL/Phase minimum-phase measurements and the “acoustic centre” offset, where “offset” is defined as positive or negative distance to the acoustic centre from the mounting baffle.

https://www.bodziosoftware.com.au/IHBT_White_Paper.pdf
https://www.bodziosoftware.com.au/Automated_IHBT.pdf

Regarding Item 2, 3 and 6

Obviously, one would have to record the original measurement conditions, such as the dimensions of the front baffle, and driver location on the front baffle. It goes without saying, that measurements are conducted on-axis in free-field. Why do we need this?.

Let’s assume, that we have completed Item 1 above. So, that driver mounted in its enclosure, has been measured at, say 1m distance. The measurement result includes diffraction effects for this particular driver location on the front baffle, the size of the front baffle and measurement distance. Given all the above, we can calculate the diffraction effects and subtract them from the measured SPL/Phase curve. What’s left is a “diffraction-less” SPL/Phase transfer function. That’s exactly what we need, because now, we can design different baffle size and shape, place the driver in different location on the baffle, and re-calculate the new diffraction curve. And then add this new curve to the “diffraction-less” SPL/Phase curve.

In summary, we can take minimum-phase measurements performed on one baffle, and transfer those onto a different baffle. This is actually very valuable characteristics of the process. Because the driver can be measured by one user, and the data can be shared by all other users incorporating the same driver in their designs.

Regarding Item 4

Just as an example, one day, you may decide to tackle 5.1 HT system design. One possible option is to make Front-Right and Front-Left speakers as 3-way systems, the Centre Channel as 2-way D’Appolito configuration and Rear-Right and Rear-Left as smaller, 2-way systems.

The design would be less time consuming, if you incorporated the same, trusted tweeter in all boxes. The tweeter will interface with different drivers in each box. In the 3-way system, the tweeter interfaces with a midrange driver, in the D'Appolito system, that tweeter interfaces with two woofers, and in the 2-way system, the tweeter interfaces with single woofer. All enclosures have different sizes and different driver locations. So, this is just a simple example of possible driver and mechanical variations in the design.

However, none of those are problems from modelling/design point of view. As long as you have the minimum-phase SPL/Phase curves and acoustic offsets defined as per Item 1, your CAD software will be able to model all those configurations. Without re-measuring drivers or configurations.

Regarding Item 5

We have already mentioned, that the original measurement distance between the front baffle and microphone needs to be recorded. Why? – Because we need this distance to correctly calculate diffraction of the original measurement. Once we subtract the original diffraction (and make the driver diffraction-less) we can re-calculate new diffraction at any distance we desire. Some designers prefer to optimize their systems at listening distance of 2, 3, or even 4 meters. Modelling at different distances will be facilitated in your CAD software, as long as you followed Item 1.

Regarding Item 7

Sealed-back drivers, like midrange and tweeters are not affected by enclosure volume. So, these drivers can be moved from one baffle/enclosure to another, without considerations for enclosure volume or type. Woofers are affected by enclosure diffraction differences, volume and type (e.g.: sealed or vented). Diffraction was explained above, therefore, we can explore the issue of low-frequency driver loading. Fortunately, the lumped-element TS model works quite well in the frequency range below 100-150Hz. Therefore, a woofer driver properly measured in sealed box, can be modelled in a vented box by using "splicing method". Here, the low-frequency SPL/Phase response is modelled for a vented enclosure and spliced around 100-150Hz with the measured SPL/Phase minimum-phase curve. If there is any phase discontinuity, it can be fixed with HBT. This is possible, because if you followed Item 1, then you know what the minimum-phase phase response should look like. Please note, that you would apply similar rules when dealing with Zin/Phase curves.

Regarding Item 8

Off-axis modelling is typically accomplished by approximating the driver's radiating surface with a number of discrete points and calculating combined SPL from all radiating points at any desired point in the surrounding hemisphere, accounting for ever-changing diffraction. Calculations are based on more (or less) complicated geometry. But as long as you followed Item 1, your CAD should be able to handle these calculations. Impedance curves are not affected here.

Regarding Item 9 and 10

If the drivers' motor electro-magnetic, material and mechanical data is included in the driver's characterization, then your CAD software may be able to model suspension and BL-related performance for Large-Signal Analysis. This is outside the scope of this paper, and is only mentioned here for completeness.

Regarding Item 11

There is some value in modelling loudspeaker system performance somewhat outside the designated operating bandwidth. The bandwidth proposed in Item 11 is just one of the options.

Regarding Item 12

One of the most useful test signals in electronics is a humble square wave. The “ideal” square wave is a superposition of an infinite number of sine waves, each contributing its required amplitude and phase. It is due to this very feature, that when passed through an audio system, the square wave can reveal time domain performance issues of the system. This is because all of its sine wave components must be passed by the system without time distortion, or different delays, in order to recombine as a square wave at the output of the system under test – your loudspeaker. https://www.bodziosoftware.com.au/Square_Wave.pdf

The linear-phase loudspeaker system is the only system that will reproduce square wave. And not only that, it will correctly reproduce impulsive sounds, undistorted “punch”, it will aid localization of the sound sources, removes “flobby” bass and more.

The loudspeaker will maintain its linear-phase characteristics over significant listening angle. https://www.bodziosoftware.com.au/Linear%20Phase%20Loudspeakers.pdf

A simple method of designing the linear-phase DSP loudspeaker system is to (1) equalize driver’s SPL, then (2) invert driver’s phase response. Each driver in the system is treated the same way, but separately. Each driver becomes an on-axis sound source with flat SPL and flat phase. Finally, acoustic offsets are equalized for the listening area by adding appropriate small delays. Done.

Given the above, once again, drivers characterized as per Item 1, are ready to go into the CAD modelling process right away, without any other “relative” considerations.

Example of a current driver characterization

Shown below is an example of another loudspeaker. This time, it’s currently available JBL 18” Low Frequency Transducer, 2241H. BTW – it’s one of the best 18” drivers I have ever seen. I use two of them in separate boxes in my bass guitar rig.

JBL
PROFESSIONAL

2241H 460 mm (18 in) Low Frequency Transducer

Professional Series

Key Features:

- 600 W continuous pink noise power capacity
- 100 mm (4 in) edgewound aluminum ribbon voice coil
- 30 Hz - 3 kHz response
- 98 dB sensitivity, 1 W, 1 m (3.3 ft)
- SFG magnet structure with patented Vented Gap Cooling™ technology[1]

Specifications:

Nominal Diameter:	460 mm (18 in)
Rated Impedance:	8 ohms
Power Capacity[1]:	600 W continuous pink noise
Sensitivity[2]:	98 dB SPL, 1 W, 1 m (3.3 ft)
Frequency Range[3]:	30 Hz - 3 kHz
Power Compression[4]	
at –10 dB rated power (60 W):	0.8 dB
at –3 dB rated power (300 W):	2.6 dB
at rated power (600 W):	4.3 dB
Distortion[5]	
2nd harmonic:	$\leq$1.0%
3rd harmonic:	$\leq$1.0%
Highest Recommended Crossover:	800 Hz
Recommended Enclosure Volume:	140-340 l (5-12 ft^3)
Effective Piston Diameter:	397 mm (15.6 in)
Maximum Excursion Before Damage (p-p):	40 mm (1.6 in)
Minimum Impedance:	6.0 ohms ± 10% @ 25°C
Voice Coil Diameter:	100 mm (4 in)
Voice Coil Material:	Edgewound aluminum ribbon
Voice Coil Winding Depth:	19.05 mm (0.75 in)
Magnetic Gap Depth:	8.1 mm (0.32 in)
Magnetic Assembly Weight:	6.8 kg (15 lb)
Bl Factor:	19.2 N/A
Effective Moving Mass:	0.145 kg
Positive voltage on BLACK terminal gives forward diaphragm motion.	

[1] AES standard (50-500 Hz).

[2] Sensitivity is based on a swept 100 Hz to 500 Hz signal for an input of 2.83 V @ 8 ohms or 2.0 V @ 4 ohms.

[3] Frequency range is defined as the frequency extremes where the response is -10 dB from the rated sensitivity.

[4] Power compression is the sensitivity loss at the specified power, measured from 50 to 500 Hz, after a 5 minute AES standard (50-500 Hz) pink noise preconditioning test at the specified power.

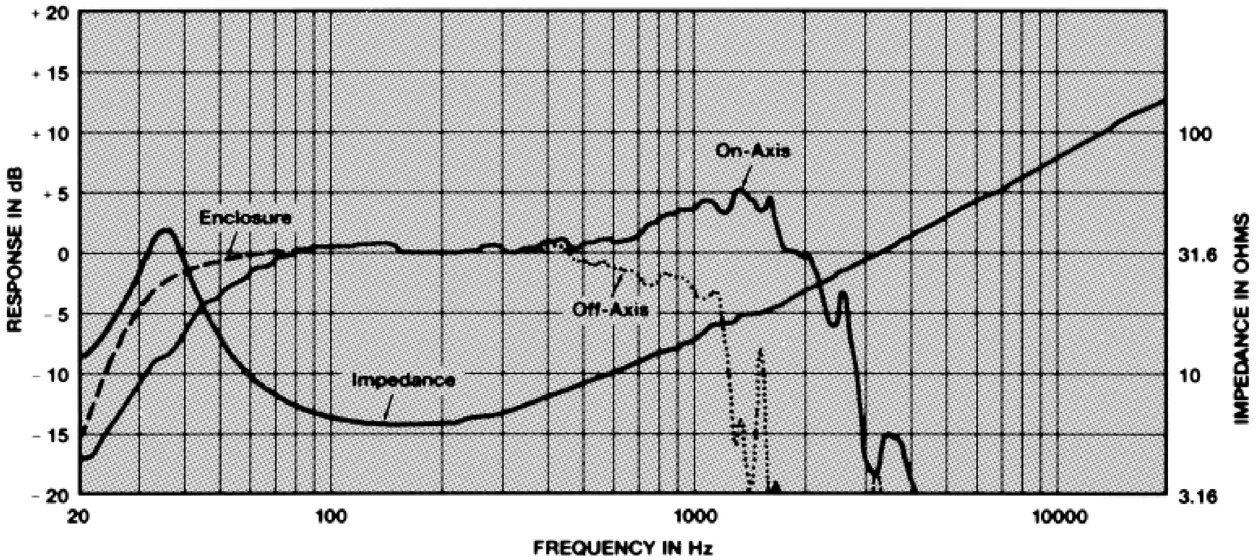
[5] Distortion is measured at -10 dB rated power, from 100-500 Hz.

THIELE/SMALL PARAMETERS[6]:	
f_s:	35 Hz
R_e:	5.0 ohms
Q_{ts}:	0.40
Q_{ms}:	5.7
Q_{es}:	0.43
V_{as}:	310 l (11.0 ft^3)
S_D:	0.124 m^2 (192.4 in^2)
X_{max}:	7.6 mm (0.30 in)
V_D:	942 cm^3 (57.7 in^3)
L_e:	1.75 mH
η_o (Half space)[2]:	2.9%
P_e (Max)[1]:	600 W continuous pink noise
MOUNTING INFORMATION:	
Overall Diameter:	464 mm (18¼ in)
Bolt Circle Diameter:	441 mm (17⅜ in)
Baffle Cutout Diameter	
Front Mount:	427 mm ($16\frac{13}{16}$ in)
Rear Mount:	428 mm ($16\frac{55}{64}$ in)
Depth[7]:	191 mm (7½ in)
Volume Displaced by Driver:	8.51 (0.3 ft^3)
Net Weight:	10 kg (22 lb)
Shipping Weight:	10.9 kg (24 lb)

[6] Thiele/Small parameters are measured after a 2 hour exercise period using a 600 W AES power test and will reflect the expected long term parameter values once the driver has been installed and operated for a short period of time.

[7] Clearance of at least 76 mm (3 in) must be provided behind the magnet assembly and the gap vents to allow sufficient air circulation and proper cooling to take place.

Typical Response and Impedance Curves, Enclosure Volume and Port Tuning



Frequency response contour of the 2241H taken in a hemispherical free-field environment, a closed box of 280 l (10 ft^3) internal volume enclosing the rear of the driver. Measured response of a typical production unit, including all peaks and dips, does not deviate more than 2 dB from the above curve. The dotted line represents measured 45 degree off-axis response. The dashed curve represents the response when the driver is mounted in a 280 l (10 ft^3) vented enclosure tuned to 30 Hz using a port with an area of 320 cm^2 (50 in^2) and a length of 20 cm (8 in). The impedance magnitude curve is measured in free-air.

Please note, that the driver was measured in anechoic chamber in sealed and vented enclosures of 280lt volume.

Conclusions

For accurate design, one will need accurate measurements. For efficient design, you'll need a database of drivers with accurate measurements and **pick-and-place** approach to achieve first-cut design stage - **fast**.

There is a simple, low cost way of standardizing and publishing the essential on-axis measurement results of loudspeaker drivers. Such measurement results are referenced to a common and clearly defined minimum-phase response and the associated point in space – acoustic centre. If implemented, either by loudspeaker manufacturers, or as DIY community shared measurements, this process has the potential of reducing developmental costs, reducing development time, increase design freedom, and increasing accuracy of the modelling process.

The method described in the previously mentioned papers will correctly extract minimum-phase response, even from tweeter's SPL measurements restricted to Nyquist Frequency of 24kHz (half the sampling frequency of 48kHz). The bulk of the method is automated, and can be implemented on a typical MLS or ESS dual-channel measurement system. This is the essence of this method – minimum-phase response and the acoustic centre are measurable using a very unsophisticated test equipment. All you need is an old Windows 7/10 PC with a reasonable sound card to run the measurement system. It is really as simple as that.

As explained in the paragraphs above, loudspeaker driver measurements taken at one specific set of test conditions, can be “deconstructed” and then “reconstructed” for another set of test conditions, for the purpose of achieving the first-cut design. Therefore, it makes sense to measure the driver only once, and then adopt/modify these results to your individual circumstances.

As shown in the above example of the JBL brochure (and many others, not shown here), loudspeaker manufacturers already measure their drivers under some acoustically favourable test conditions. So, the SPL curve is already available. But, you are only being shown enough to entice you into purchasing the driver. What is needed, is the design data that would allow you to proceed with CAD modelling.

With a minimum cost and effort, and using the method described above, one could easily extend the SPL measurement into SPL/Phase measurement and store automatically extracted minimum-phase and SPL responses even in a TEXT file. This file would be published on the manufacturer’s website for each driver.

Imagine that happening ☺.

Thank you for reading

Bohdan

Acknowledgments of public domain information

I wish to acknowledge the usage of **JBL data brochure for the 2241H driver**.
I wish to acknowledge the usage of **Phillips Components And Materials data, Part 3b, from October 1978 – Loudspeakers**