Distortion and Power Compression in Low-frequency Transducers

1. Introduction:

All too often, consultants and sound contractors are concerned with only the input power rating and Thiele-Small parameters of low-frequency transducers. Certain other important aspects of performance are not adequately spelled out by the above quantities, namely mid-band distortion and power compression at high drive levels. JBL LF transducers are noted for their exemplary performance in both of these areas, and in this Technical Note we will examine the details of design and construction which result in this degree of performance.

2. Ferrite versus Alnico V: Distortion in the Mid-band:

For years JBL used Alnico V in the design of all 50 mm (2 in), 75 mm (3 in), and 100 mm (4 in) voice coil transducers. We had analyzed the various ferrite materials which were available, and we had tentatively come to the conclusion that we could make lower distortion devices by staying with Alnico V. Ferrite was certainly cheaper, and the bulk of the loudspeaker industry had already moved in that direction.

Our continuing research in magnetics indicated that some of the faults we had observed in ferrite magnet structures were not inherent in that material, but rather were due to its implementation. Our research was quickened by the worldwide cobalt shortage, and in 1978 JBL introduced its first Symmetrical Field Geometry (SFG) magnet structures. We had succeeded in improving on our older Alnico V designs, and the data of Figure 1 summarizes our results. Here, we have taken the same moving system and compared its performance in the following three magnetic assemblies:

1. Conventional JBL Alnico V assembly
2. Conventional ferrite assembly
3. Optimized ferrite assembly with undercut pole piece and flux stabilizing ring

In Figure 1A we show the performance of the 128H cone assembly (the LF element in the 4411 monitor loudspeaker) as mounted in the traditional Alnico V structure. Distortion components have been rasied 20 dB for ease in reading. Power input is ten watts. Note that second harmonic distortion above 100 Hz is just about 40-to-50 dB below the fundamental, indicating distortion below 1%.

When the same moving structure is placed in a conventional ferrite structure with the same flux density, as shown at B, we see that the mid-band distortion is 35 dB below the fundamental, indicating distortion of about 2%.

When the same moving system is placed in the optimized ferrite structure, as shown at C, the second harmonic distortion components have all but fallen off the page, and the distortion is in the 0.3% range.

The differences between conventional ferrite structures and JBL's Symmetrical Field Geometry (SFG) design are shown in Figure 2. The undercut pole piece provides a major improvement in second harmonic distortion, inasmuch as it creates symmetrical flux lines on both sides of the pole piece and top plate. However, this was not sufficient to match the performance of our older Alnico designs.

There were two remaining problems, inductance modulation and flux field modulation, and we went back to the work of Michael Faraday to solve them. We placed an aluminum ring at the base of the pole piece. This ring, or "Faraday loop," links the flux and provides coupling with the voice coil. Its cross-sectional area is about one square centimeter, and its resistance is less than one-thousandth ohm. Quite high currents may flow through it, but power loss is minimal.

Inductance modulation occurs because the voice coil "sees" more iron when it moves into the gap than it does when it moves out of the gap. With the shorted turn in place, we have in effect a transformer, as shown in Figure 3, with a very low resistance in the secondary

Figure 1. Response of 128H Transducer Moving System Placed in Three Different Magnet Structures. (Measured at 1 meter with 10 watts Input.)

A. JBL Alnico V Magnet Sturcture.
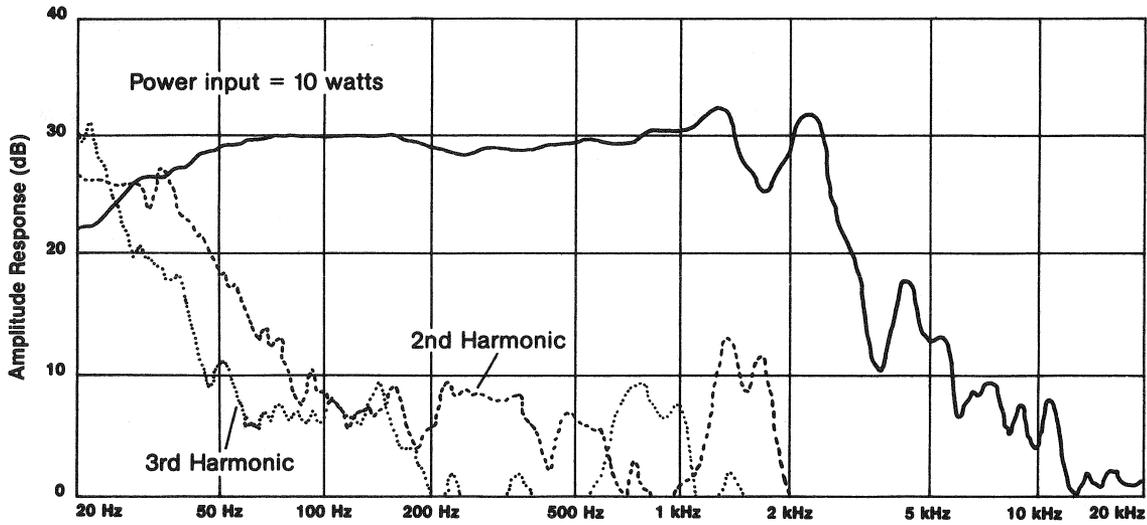
B. Conventional Ferrite Structure.
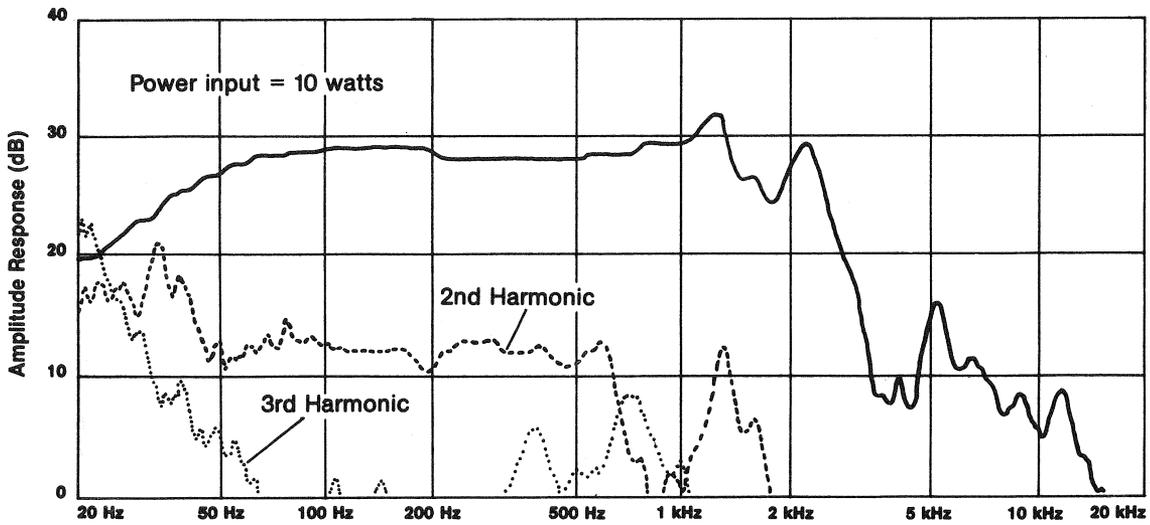
C. Optimized JBL Ferrite Structure (SFG).
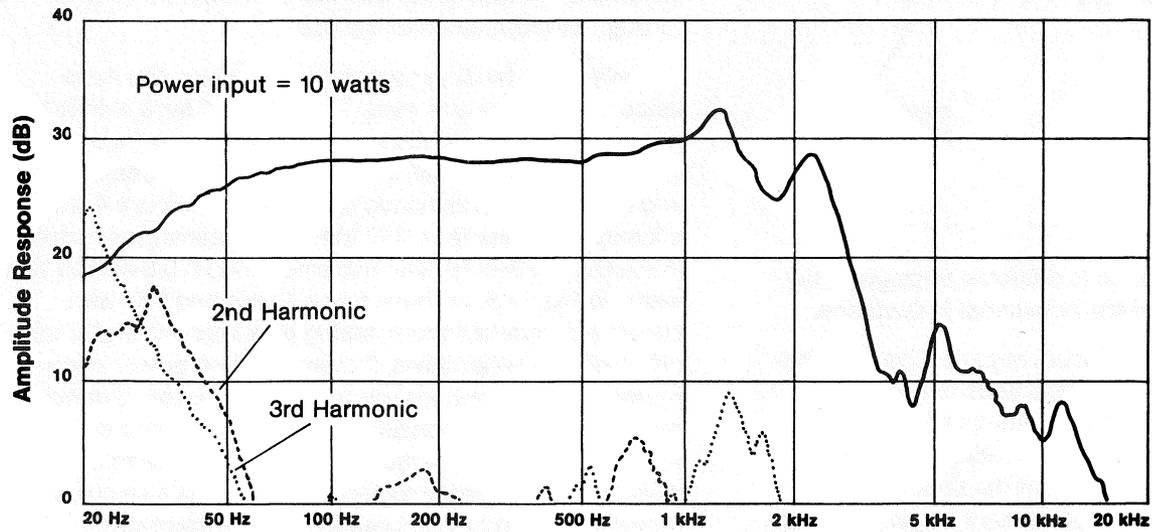
Figure 2. Comparison of Conventional Ferrite Magnet Structure and JBL's SFG Structure.
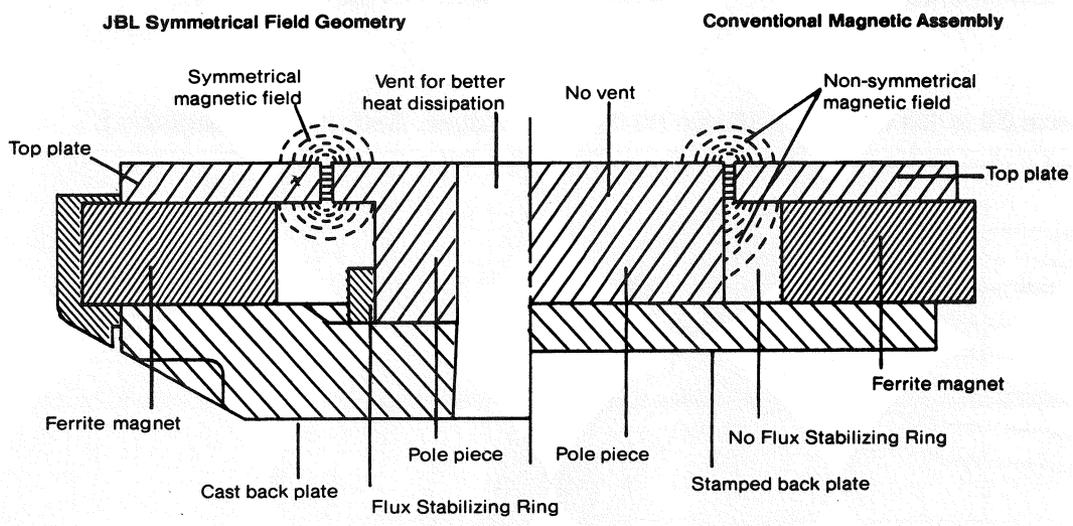
Figure 3. Reduction of Inductance Modulation through Use of a Shorted Turn.

Voice Coil
(primary; non-linear
inductance)

Shorted Turn
(secondary; very low
resistance)
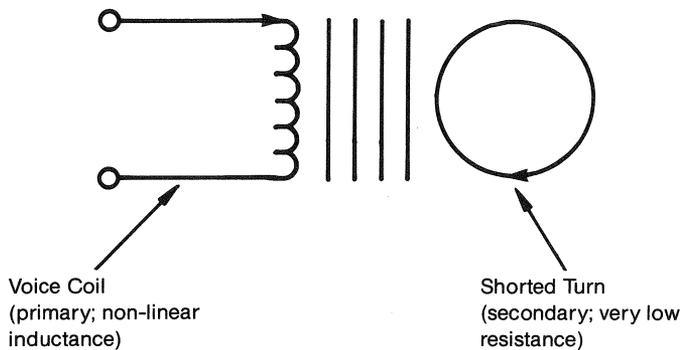
winding. The low resistance is reflected through to the primary and swamps out the non-linear inductance.

Flux field modulation occurs because the flux generated by current in the voice coil adds to that of the magnet on one half cycle and subtracts on the other half cycle. The resulting shift in the operating point causes second harmonic distortion. When the shorted turn is in place, current is induced which creates its own alternating flux opposite to that generated by the voice coil. Thus, the flux field modulation is minimized.

We do not know of any other domestic manufacturers of professional LF transducers who make use of both undercut pole pieces and flux stabilizing rings.

3. Power Compression at High Output Levels:

A. Description of Power Compression:

For short duty cycles, most LF transducers intended for professional use can stand power input up to ten times their nominal power rating, assuming of course that the input signal does not result in voice coil excur-

sions exceeding the design limit of the device. The key here is the duty cycle. In normal professional usage, especially in demanding music reinforcement, the required duty cycle is nearly continuous.

Since most LF loudspeakers are far less than 10% efficient, it is clear that the bulk of the power input must be dissipated as heat. The heat is generated at the voice coil and is a direct consequence of current flowing through the resistance of the coil.

While the heating process is underway, the resistance of the voice coil rises. The "benefit" here is that the voice coil will tend to draw less current—and thus attempt to protect itself. The drawback is in sonic terms, and it is known as dynamic compression. Figure 4 shows a family of curves for a 380 mm (15 in) transducer driven in successive 3-dB power increments from 0.8 watt to 100 watts. In Figure 5, we have taken 1-watt and 100-watt curves and overlaid them, taking into account the 20 dB difference between them. If there were no power compression the two curves would overlap exactly. But note that there is a fairly consistent 1.25 dB difference between them. In general, dynamic compression will be minimal at transducer impedance peaks, since there is less current drawn. Conversely, compression will be greatest in regions of minimum impedance, because more current will be drawn.

The effect may be cumulative with time, as shown in Figure 6. Here, response sweeps were made with 200 watts nominal power input at 20 minute intervals through a 100-minute time span. The curves taken at 80 and 100 minutes were observed to overlay almost exactly, indicating that the voice coil and magnetic structure had reached thermal equilibrium. Note that the total power compression at 200 watts input is about 3½ dB in the mid-band. This is exactly what would happen in acutal musical performance if the transducer were being subjected to continued 200-watt power input.

Figure 4. Response Curves from 0.8 to 100 watts for a 380mm (15 in) LF Transducer. Bottom line is 80dB(SPL).

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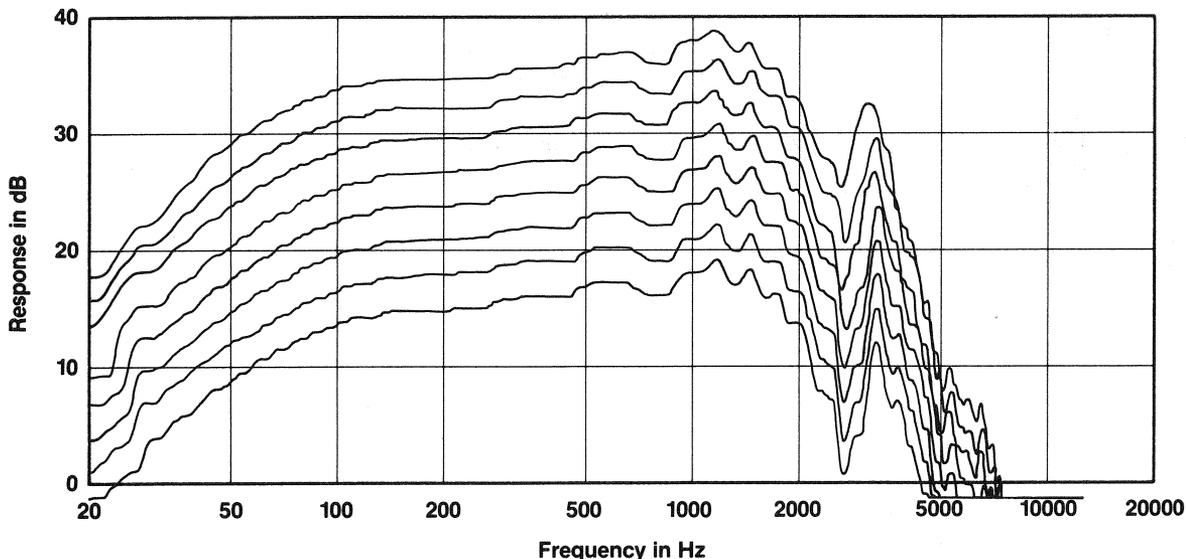
Figure 5. Response Curves for 1 watt and 100 watts, Adjusted by 20 dB. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB for 100 watts.
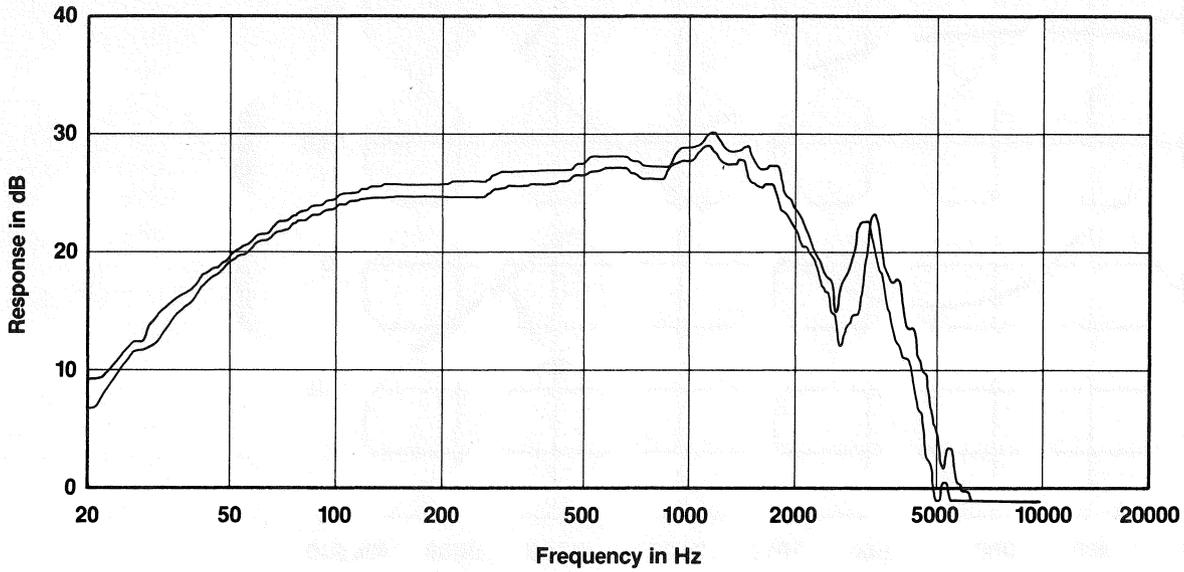
Figure 6. Cumulative Effects at 200 watts input. Bottom Line is 90 dB(SPL).
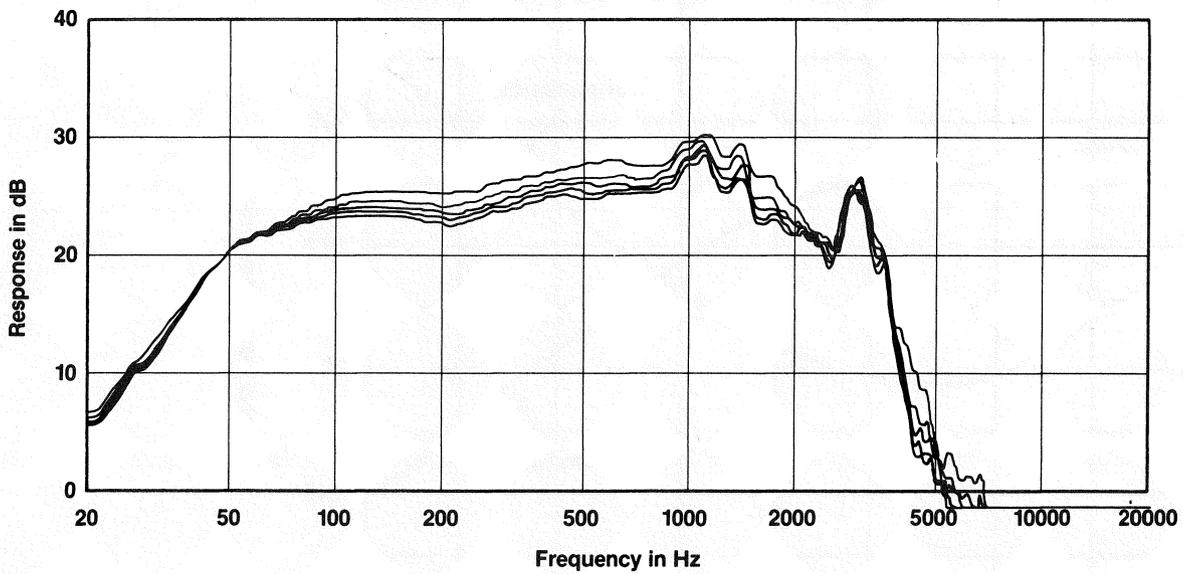
Figure *7.* Typical LF Alignment Shifts.

A. JBL 2240H Optimized at 27°C (80°F).
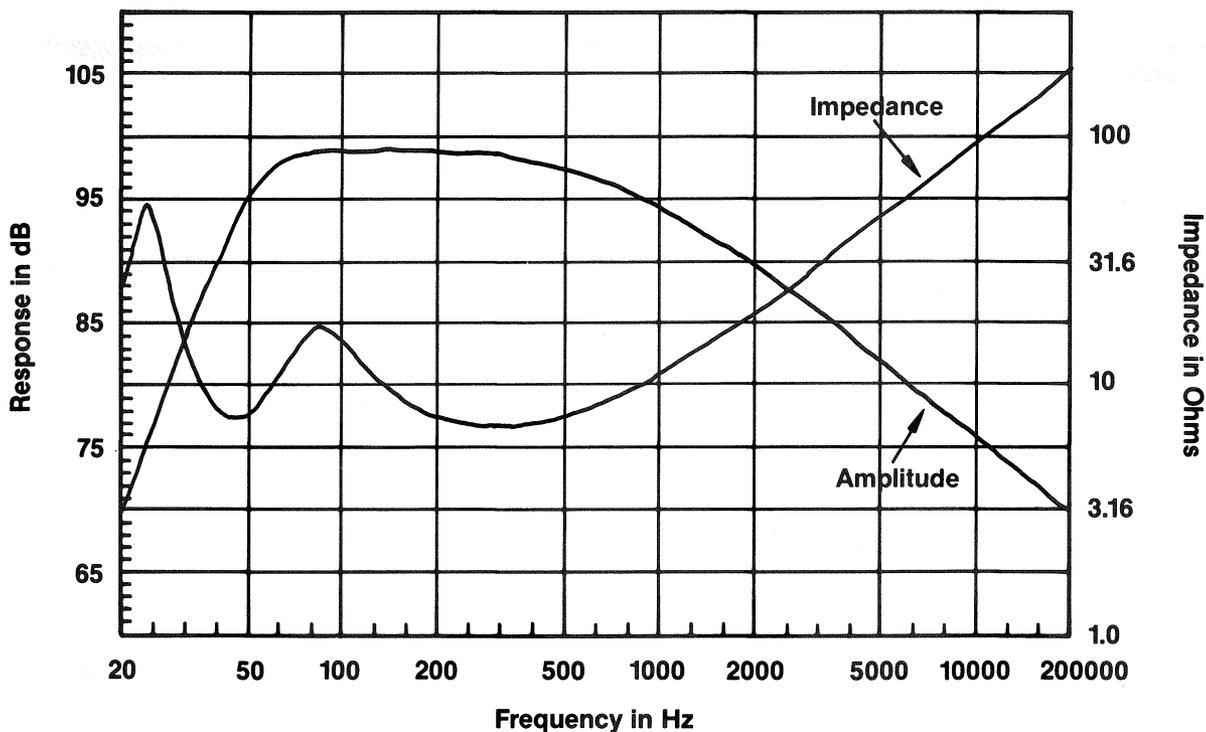
B. JBL 2240H with 150°C (302°F) Voice Coil Temperature.

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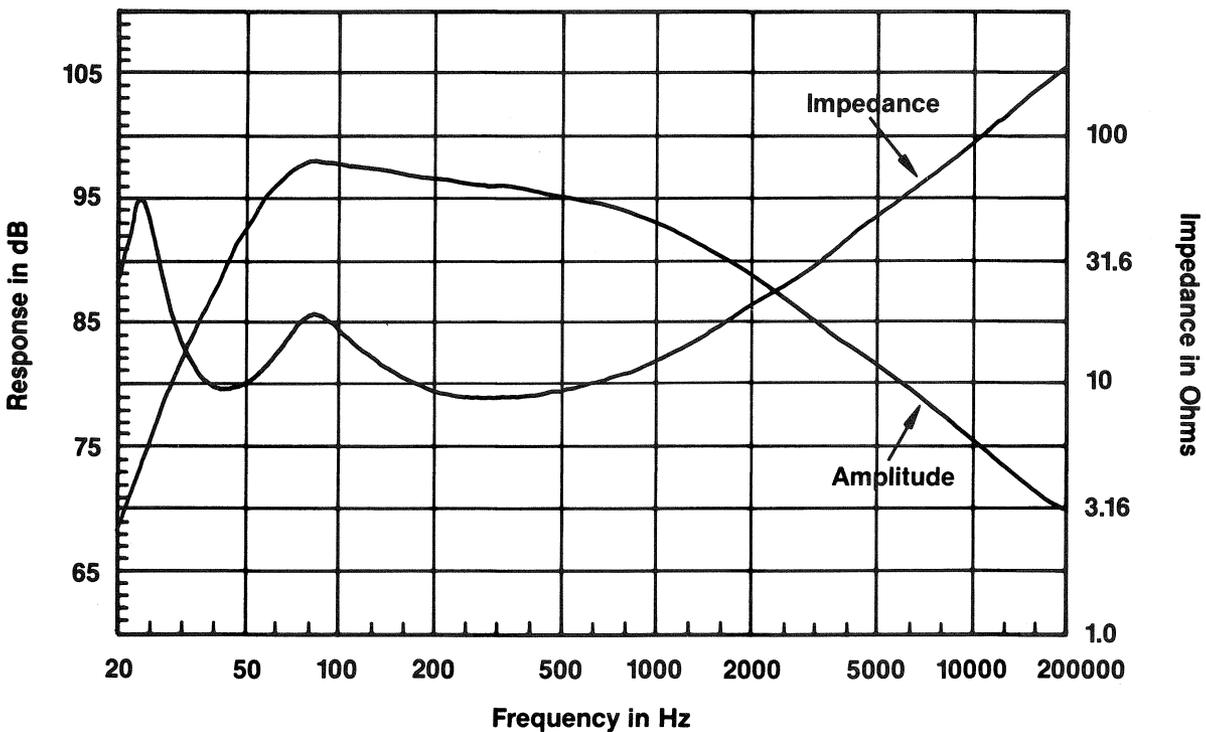
B. Magnitude of Resistance Shift:

The increase in resistance over that measured at room temperature is given by the following equation:

$$R_T = R_t \left\{ 1 + \alpha \, (T_T - T_t) \right\}$$

where α is the temperature resistance coefficient, T_t is room temperature and T_T is some elevated temperature, both in degrees Celsius. For aluminum and copper, the materials normally used for voice coils, the value for α is about 0.004 per degree Celsius.

Room temperature is usually about 20 degrees Celsius, and it is not unusual for voice coil temperatures to reach 200 degrees Celsius. Under this condition, a voice coil with resistance of 6 ohms at room temperature will increase to 10.3 ohms. High powered voice coils may operate as high as 270 degrees Celsius, and under this condition the resistance will be double what it was at room temperature.

Since efficiency is inversely proportional to voice coil resistance, it is obvious that there can be some remarkable shifts in transducer efficiency as a fraction of voice coil temperature increase. Voltage sensitivity will be affected somewhat differently, since it is a function of both efficiency and transducer impedance.

LF alignments will also be affected by the resistance shift. The curves shown in Figure 7 are typical of what may happen.

C. Heat Transfer:

The way to reduce dynamic compression is through increased heat sinking and minimizing temperature rise in the first place. It is in this area where JBL's 100 mm (4 in) voice coils have a natural advantage over the smaller diameter voice coils used by the bulk of the industry.

Assume that we are going to design a LF transducer and that we have our choice of making the voice coil either 63 mm (2.5 in) in diameter or 100 mm (4 in) in diameter. The choice of the smaller diameter will result in a smaller magnet and will of course cost us less. But for a given voice coil resistance and a given axial length of the coil, the wire chosen for the larger diameter voice coil will be $\sqrt{4/2.5}$, or 1.26 times greater in cross-sectional area. This results in a proportional reduction in resistance per unit length. Less resistance translates into greater current capacity, and thus less heat.

The increased surface area of the larger voice coil will promote better heat transfer as well.

4. Suspension Non-linearities at High Power Inputs:

If a LF transducer is driven at high levels in the region of resonance, the voice coil will tend to leave the magnetic gap at peak displacements. This will cause some loss of magnetic flux cutting the voice coil, and there will be a loss of Bl product. When this happens, there will be a drop in the motional impedance of the transducer, causing it to draw more current, thus moving even farther out of the gap. The transfer characteristic is altered, as shown in Figure 8, and generous amounts of second harmonic distortion will be produced. There is also a tendency for the cone to show DC offset, migrating out of the gap during large excursions.

Harwood has described this action in detail (see reference) and suggests the use of spiders (inner suspension) which exhibit progressively increasing stiffness. When this is done, a significant degree of distortion cancellation takes place, and the loudspeaker's transfer characteristic can be maintained linear over a larger displacement range.

Figure **8. Magnetic and Suspension Non-linearities.**
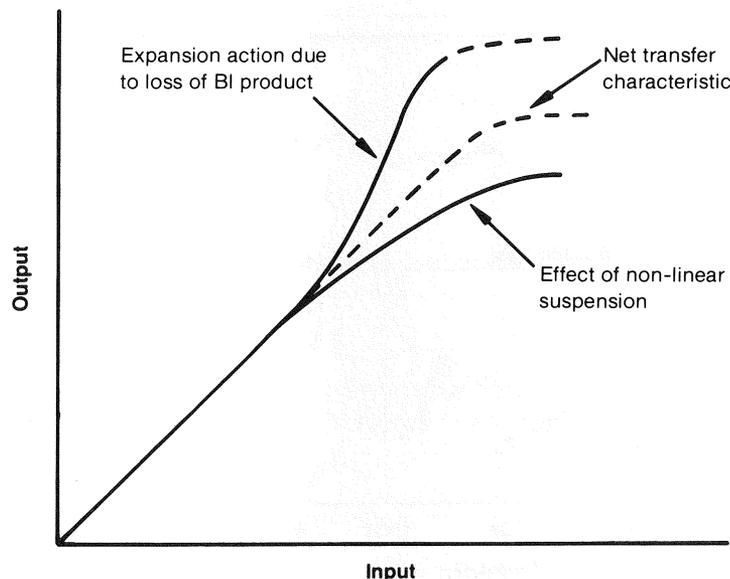
In recent years, most of JBL's LF transducers have been redesigned with such spiders; however, for certain musical instrument applications, the development of second harmonic distorion may be a desirable sonic characteristic and intentionally designed into the product.

5. Competitive Comparisons:

In this section we will examine 100-watt distortion data as well as dynamic compression data for a number of transducers. Distortion components have all been raised 20 dB for ease in reading. All curves were run at a distance of one meter, and the transducers were mounted in a 280 liter (10 cubic foot) enclosure flush mounted in a large flat baffle.

A. 100-watt Distortion Data:

Figures 9 through 14 show 100-watt distortion data for six LF transducers. We will now comment on the data in detail:

JBL E140-8 (Figure 9):

Primary application: musical instrument (bass guitar).

Frequency response: quite smooth out to 2 kHz with a slight rise in the 1-to-2 kHz octave; appropriate for its application.

Distortion: remains below 3% in the 200 Hz to 1 kHz range.

DC offset: substantial, as indicated by rise in second harmonic in 60 to 180 Hz range; appropriate for its application; designed into the tranducer to add warmth and "punch" to bass guitar sound production.

JBL 2225H (Figure 10):

Primary application: sound reinforcement.

Frequency response: exceedingly smooth out to 2 kHz.

Distortion: quite low; below 5% from 60 Hz to 4 kHz; less than 2% from 80 to 800 Hz.

DC offset: not evident.

Electro-Voice EVM-15L (Figure 11):

Primary application: musical instrument (guitar).

Frequency response: smooth to 4 kHz for extended range application.

Distortion: generally rising characteristic from 200 Hz to 2 kHz; indicative of cone breakup and lack of undercut pole piece and flux stabilizing ring; less than 5% from 80 Hz to 800 Hz; 10% from 60 Hz to 4 kHz.

DC offset: evident from second harmonic rising along with third at low frequencies; suggests some non-linear suspension action.

Figure 9. JBL E140-8 100 watt Distortion Data.

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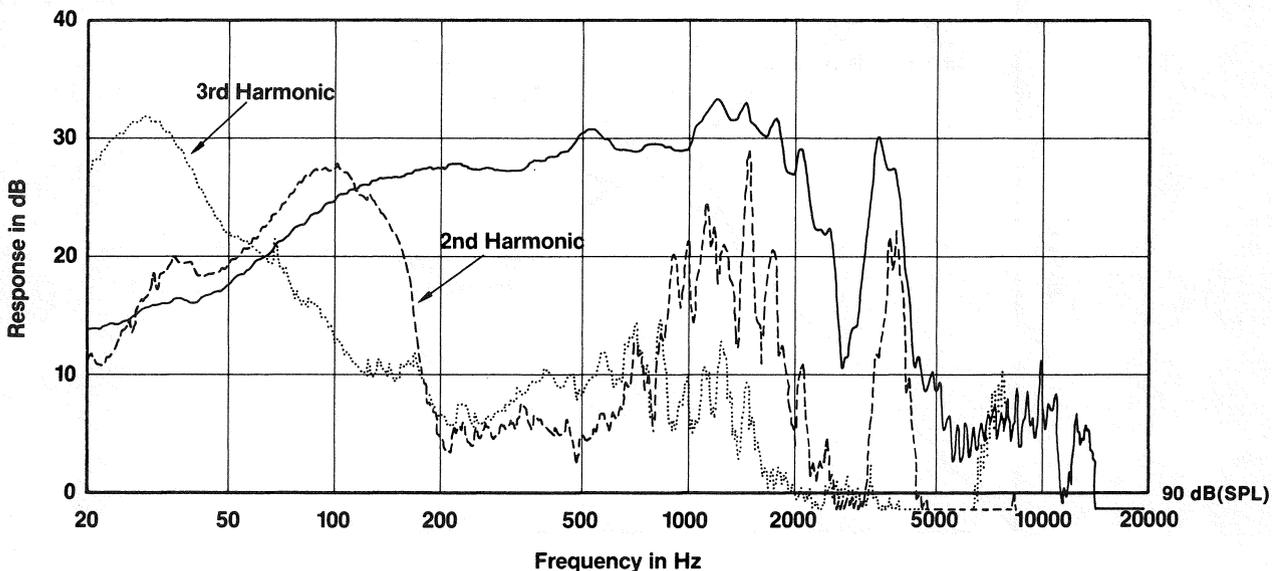
Figure 10. JBL 2225H 100 watt Distortion Data.
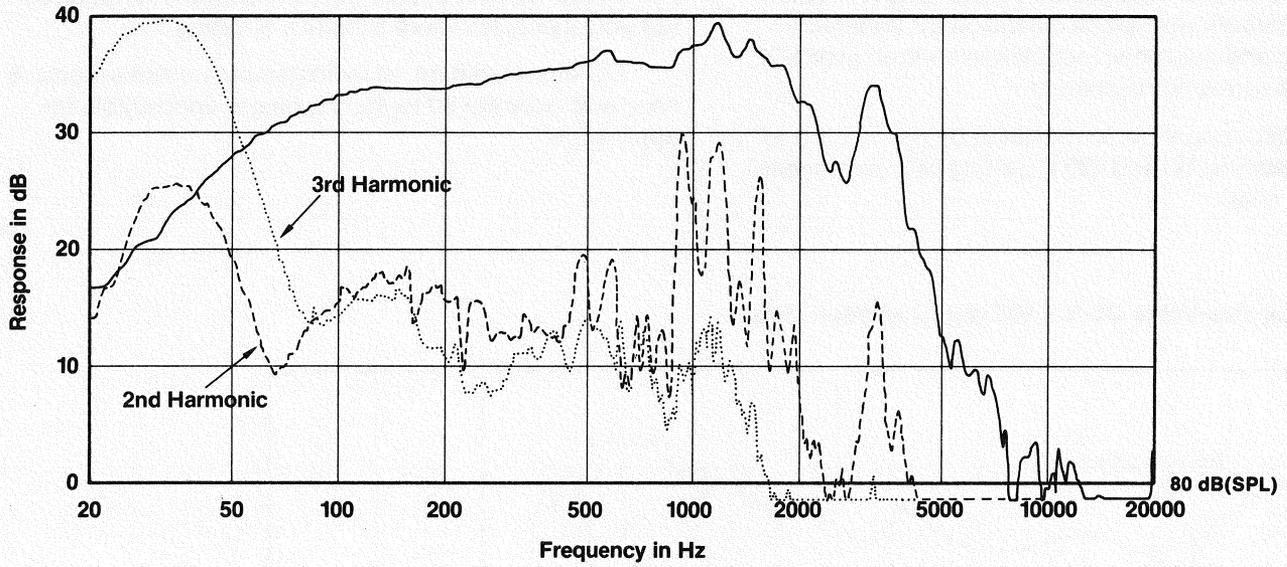
Figure 11. Electro-Voice EVM-15L 100 watt Distortion Data.
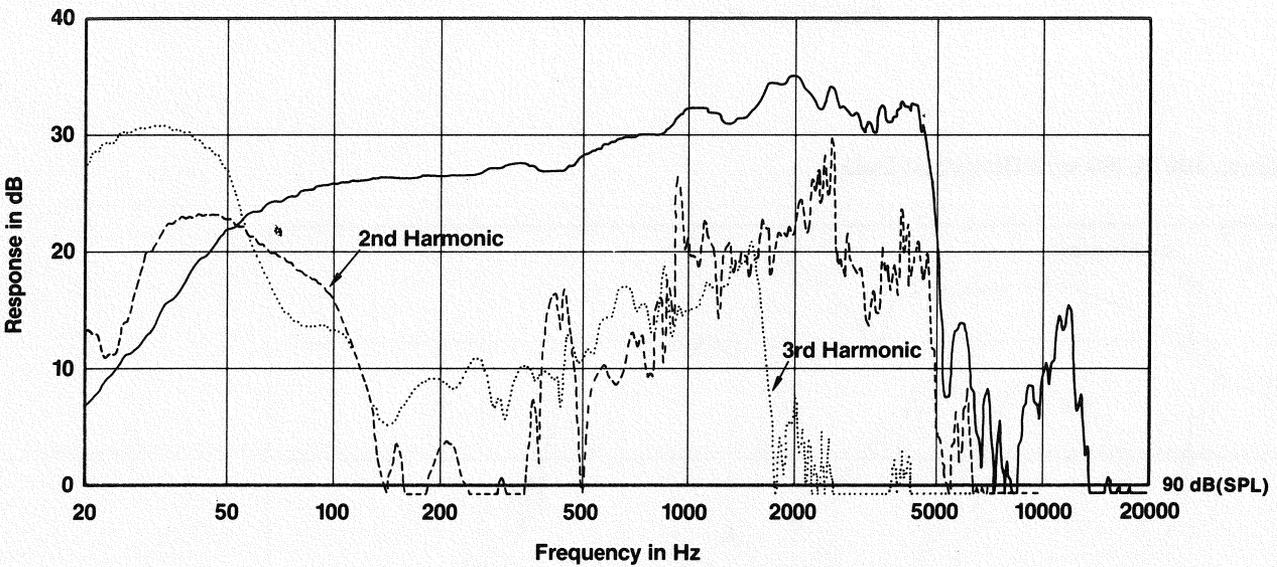
Electro-Voice DL-15X (Figure 12):

Primary application: sound reinforcement.

Frequency response: quite smooth out to 3 kHz with the exception of a surround resonance dip at 380 Hz.

Distortion: fairly high for a transducer intended for reinforcement applications (compare with JBL 2225H); transducer has no undercut pole piece; however, it does have an aluminum pole piece extension for improved heat sinking and voice coil inductance control; over 10% distortion at surround resonance.

DC offset: moderate, as indicated by rise in second harmonic between 60 and 120 Hz, along with non-linear suspension bias.

Gauss 4883A (Figure 13):

Primary application: sound reinforcement (extended bass).

Frequency response: quite jagged, due to non-linear double spider suspension.

Distortion: remains at constant 2% to 3% below 400 Hz; undesirable for application; transducer has an undercut pole piece, but there is no flux shorting ring.

DC offset: evident, as indicated by the rise in second harmonic over the 80 to 400 Hz range; undesirable for application.

Figure 12. Electro-Voice DL-15X 100 watt Distortion Data.
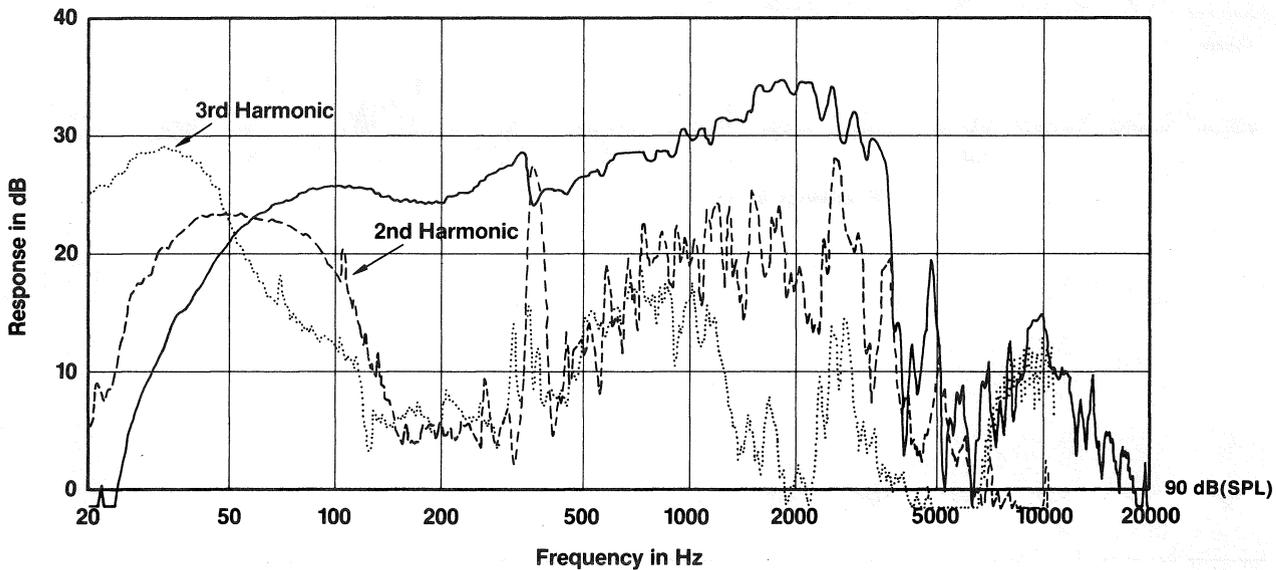
Figure 13. Gauss 4883A 100 watt Distortion Data.
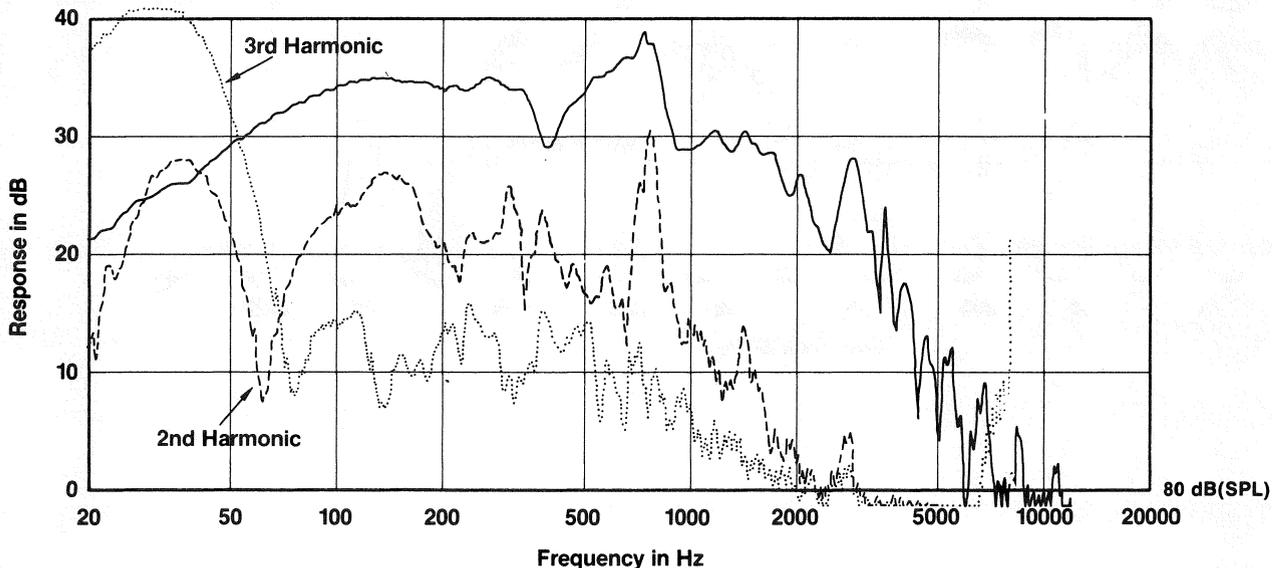
Fostex L469 (Figure 14):

Primary application: sound reinforcement.

Frequency response: significant peak in the 1-to-2 kHz not appropriate for sound reinforcement; severe surround resonance dip between 300 and 400 Hz.

Distortion: overall distortion is quite low in the mid-band.

DC offset: evident in the 60 to 150 Hz range; not appropriate for application.

B. 1-watt, 100-watt Compression Data:

Figures 15 through 20 detail the compression characteristics of these six transducers.

JBL E140-8 (Figure 15):

Voice coil diameter: 100 mm (4 in)

Compression: about 1 dB with the exception of 2.5 dB in the range of impedance minimum.

Figure 14. Fostex L469 100 watt Distortion Data.
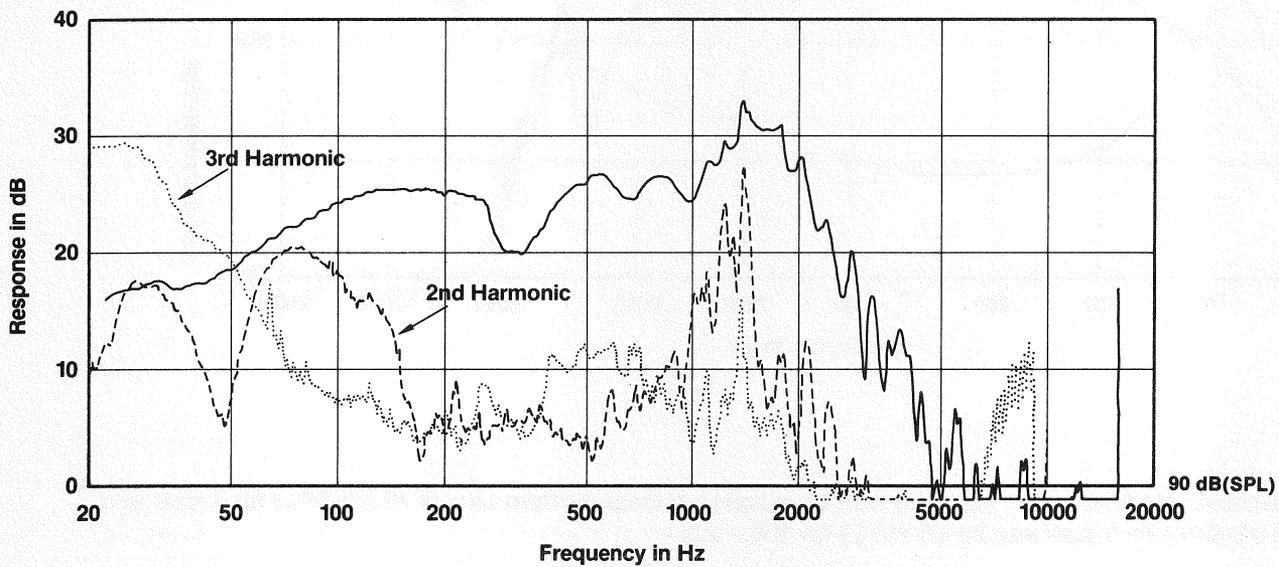
Figure 15. JBL E140-8 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 100 watts.
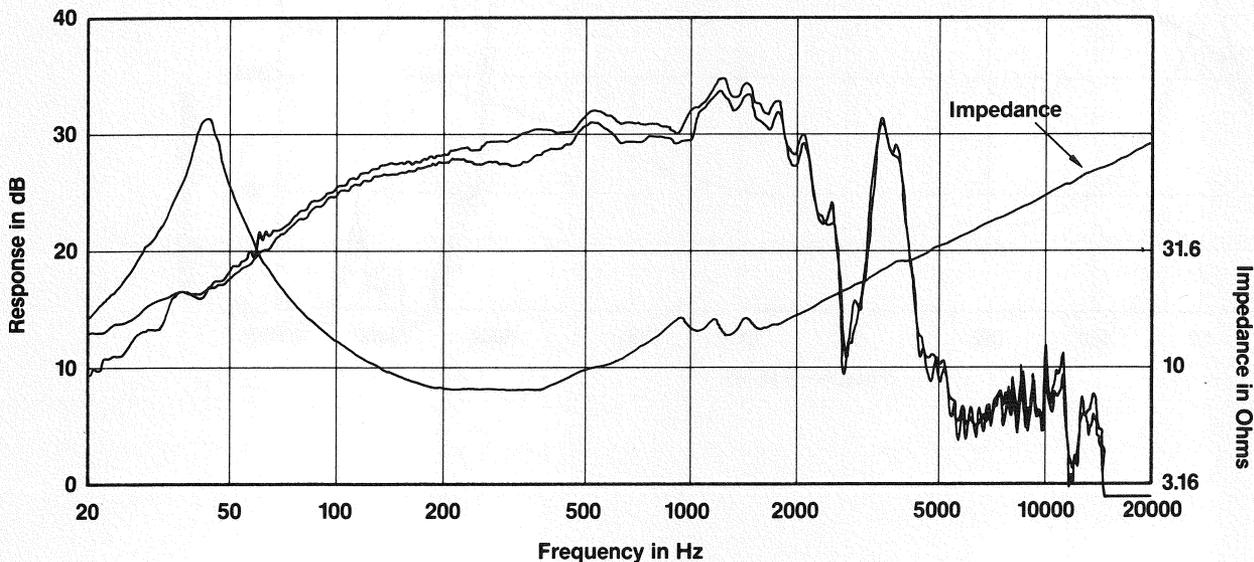
JBL 2225H (Figure 16):

Voice coil diameter: 100 mm (4 in)

Compression: just over 1 dB over most of the range.

Electro-Voice EVM-15L (Figure 17):

Voice coil diameter: 63 mm (2.5 in)

Compression: consistent 2.5 dB except at impedance peak.

Figure 16. JBL 2225H 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 100 watts.
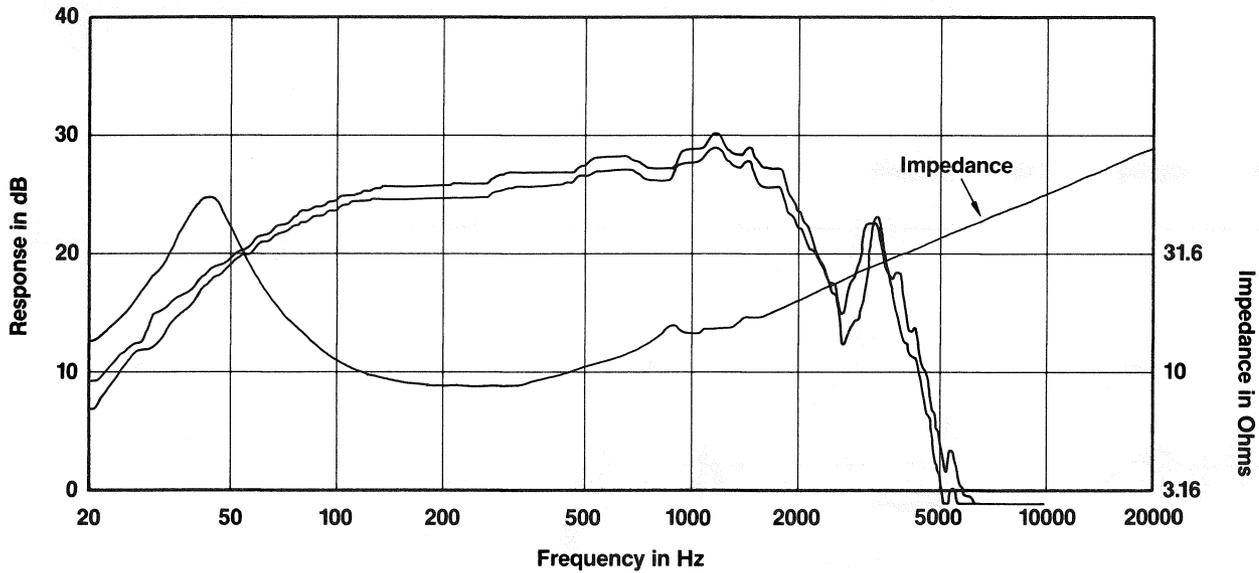
Figure 17. Electro-Voice EVM-15L 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 1 watt and 90 dB (SPL) for 100 watts.

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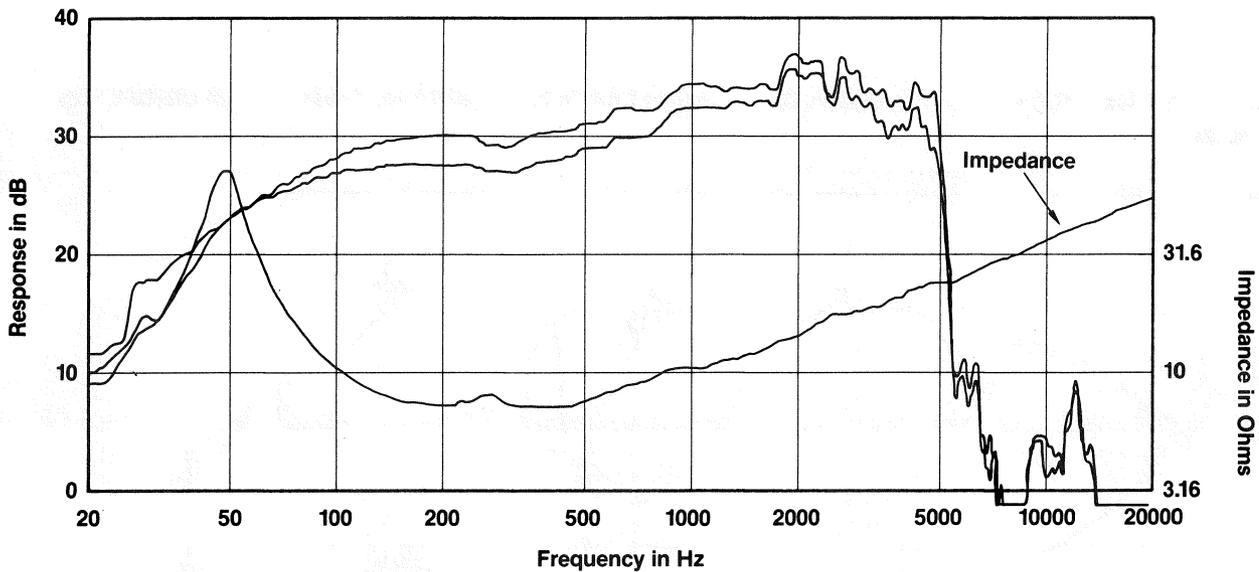
Electro-Voice DL-15X (Figure 18):

Voice coil diameter: 63 mm (2.5 in)

Compression: 2.5 to 3 dB except at impedance peak.

Gauss 4883A (Figure 19):

Voice coil diameter: 105 mm (4.125 in)

Compression: generally 1.5 dB below 200 Hz; however, above that point, the effects of complex suspension become evident.

Figure 18. Electro-Voice DL-15X 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 100 watts.
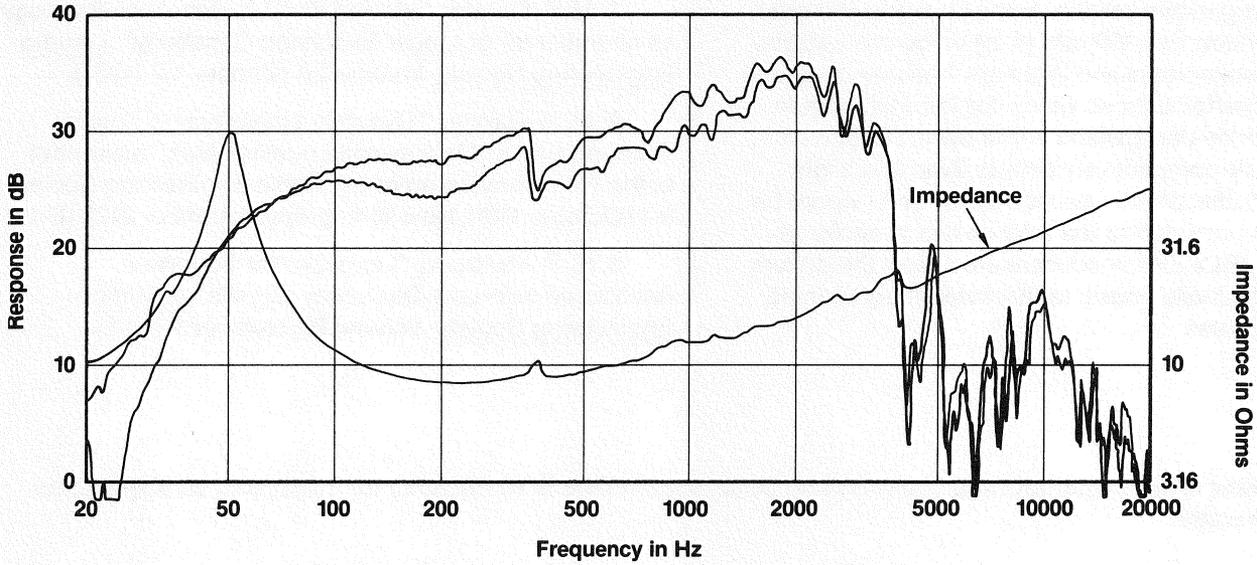
Figure 19. Gauss 4883A 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 100 watts.

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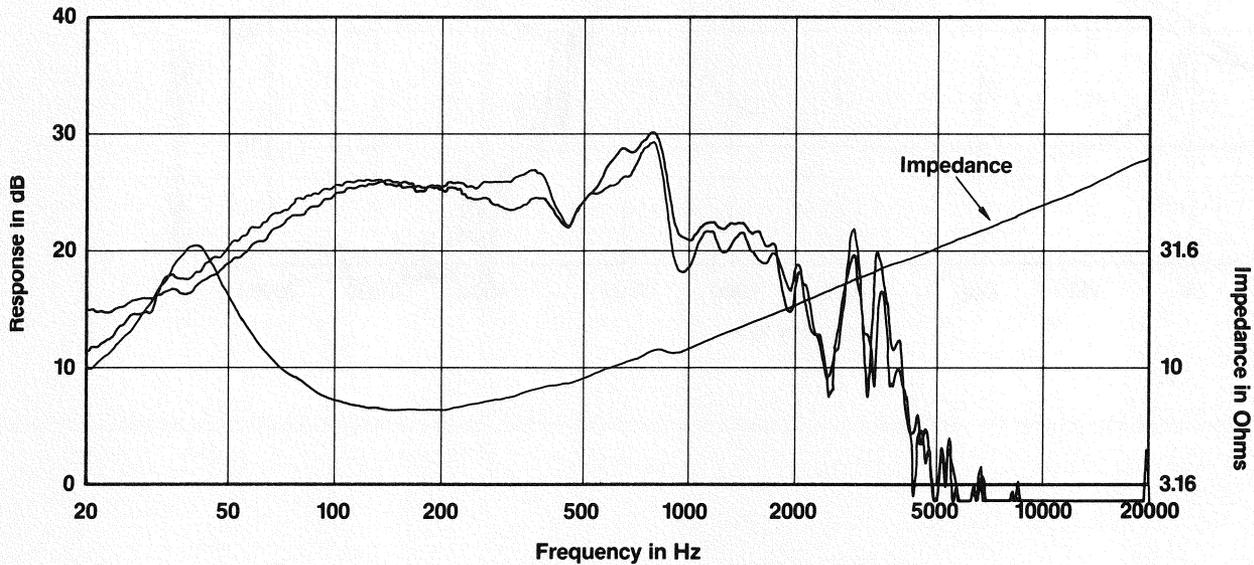
Fostex L469 (Figure 20):

Voice coil diameter: 100 mm (4 in)

Compression: generally 1.5 to 2 dB; note downward shift of the 340 Hz surround dip in the 100-watt curve; indicates mechanical instability in the surround.

6. Conclusions

In this Technical Note, we have pointed out the design aspects which have given JBL LF transducers their reputation for quality and superlative sound. As systems designers, you are expected to specify components which perform reliably and with signal integrity. It is our contention that 100 mm (4 in) voice coil designs outperform smaller ones and that high-linearity magnetic structures outperform those which exhibit flux modulation. A quick price comparison will show that JBL's LF devices are very competitively priced. Even at a slight price premium, the added cost of JBL LF units would be minimal when considering the total cost of a reinforcement system. JBL's LF transducers are in fact the drivers of choice of the major music reinforcement companies in the United States.

Remember, too, that you often have to look carefully at a LF transducer to determine the actual voice coil diameter. Most manufacturers of smaller diameter voice coils will use an oversize dust cap to hide that fact. You can always tell the true size by looking under the cone at the point where the inner suspension (spider) joins the cone.

References:

1. M. R. Gander, "Moving Coil Loudspeaker Topology as an Indicator of Linear Excursion Capability," J. Audio Engineering Society, Volume 29, Number 1/2 (1981).

2. M. R. Gander, "Dynamic Linearity and Power Compression in Moving-coil Loudspeakers," presented at the 76th Convention of the Audio Engineering Society, 8-11 October 1984, New York; preprint number 2128 (E-11).

3. H. D. Harwood, "Loudspeaker Distortion Associated with Low-frequency Signals," J. Audio Engineering Society, Volume 20, Number 9 (1972).

Figure 20. Fostex L469 1 watt, 100 watt Compression Data. Bottom Line is 70 dB(SPL) for 1 watt and 90 dB(SPL) for 100 watts.