Technical Notes Volume 1, Number 8

Characteristics of High-Frequency Compression Drivers

1. Introduction:

When a professional sound contractor or acoustical consultant specifies a JBL 2445 driver over a JBL 2425 driver, he is paying 1.5 times more. For his extra expenditure, he is getting two very important advantages: about 2 dB more level in power handling and significantly lower second and third harmonic distortion for a given acoustical power output. It is JBL's contention that the reduced distortion is the greater of these two benefits, and we believe that careful systems designers will, after digesting the information contained in this Technical Note, be more inclined toward specifying the larger diameter drivers, especially when their relatively small price impact on the total system cost is taken into account.

In this Technical Note, we will describe the operation of compression drivers in detail, focussing on those aspects which are of interest to consultants and systems designers. There is nothing mysterious about these devices, and they can be accurately described by a number of mathematical equations. These equations and the calculations made with them are included in the Appendices of this Technical Note.

2. Some Basics:

A. Physical Description:

Figure 1 shows a detailed drawing of a compression driver. A cutaway view is shown at A, and an end view of the phasing plug with diaphragm removed is shown at B. The significant physical and acoustical parameters are indicated on the drawings, and they are defined below:

R_E = voice coil resistance in ohms

l = voice coil length in meters

B = magnetic flux density in the gap in Teslas

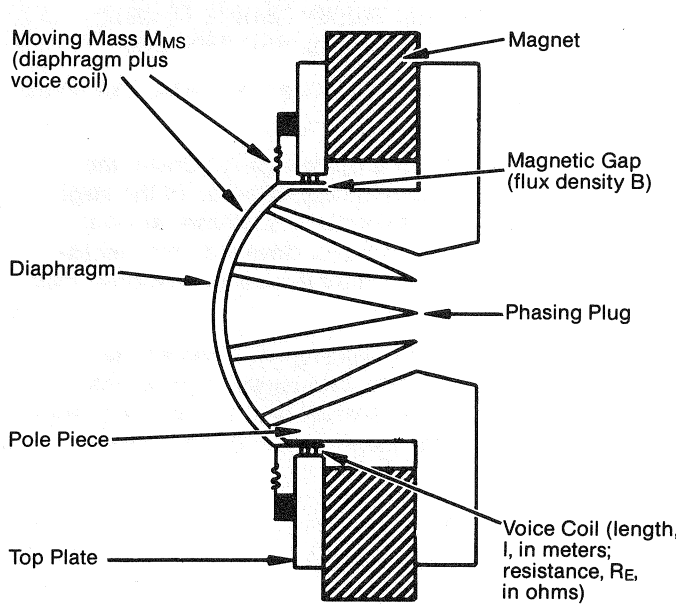
S_T = area of annular slits in phasing plug in square meters

S_D = area of diaphragm in square meters

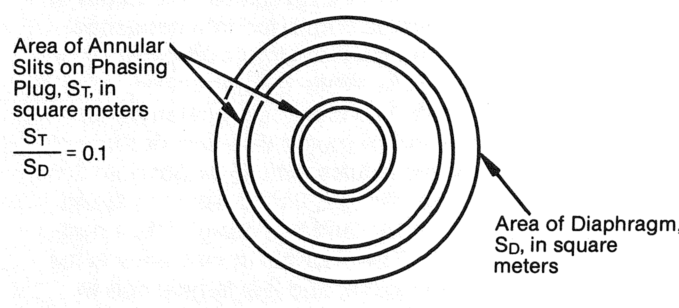
S_T/S_D = loading factor (normally equal to 0.1)

M_{MS} = mass of moving system (diaphragm-voice coil assembly) in kilograms

Figure 1: **Details of a Compression Driver**



A: **Cross-Section View**



B: **End View of Phasing Plug, Diaphragm Removed**

A compression driver differs fundamentally from other loudspeakers in that the diaphragm does not radiate directly into the air. It is placed fairly closely to a solid structure known as a phasing plug. The phasing plug has a number of openings in it, and the area of these openings is usually about one-tenth that of the diaphragm itself.

When the diaphragm is actuated by current through the voice coil, high pressures are developed in the space between the diaphragm and phasing plug because of the relatively constricted openings in the phasing plug. Such high pressures are suitable for driving horns, since the high acoustical impedance at the throat of the driver is a good match for that encountered in the throat of the horn.

B. Common Sizes of High-frequency Compression Drivers:

For compression drivers intended for high frequency use, there are three main sizes:

Small: 44 - 50 mm (1.75 - 2 in) diaphragm diameters. Examples: JBL 2425H/J: Altec 902, 908: TAD TD-2001; EV DH1506; Renkus-Heinz SSD1800; 1801; Emilar ECH175

Intermediate: 75 mm (3 in) diaphragm diameter. Examples: Altec 288, 290, 291; EV DH1012, DH2012; Emilar EC314, 320; Renkus-Heinz SSD 3300, 3301

Large: 100 mm (4 in) diaphragm diameter. Examples: JBL 2445J; TAD 4001

In general, the larger a compresssion driver, the greater input power it can handle, because of the larger voice coil and greater heat sinking. Contrary to what many people believe, the smaller drivers do not necessarily have more extended high frequency response than the larger models.

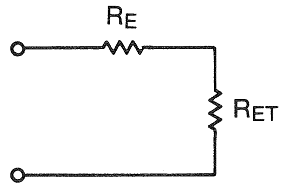
Other pertinent characteristics of a compression driver are its efficiency (which translates directly into sensitivity), extension and smoothness of high frequency response, and distortion as a function of acoustical output.

3. Efficiency:

The efficiency of a driver determines how much of the electrical input power is converted into acoustical output power. The theoretical maximum efficiency of a compression driver is 50%. While the parameters of most drivers are selected with this efficiency goal in mind, practical drivers fall short of the goal by two or three dB. Thus, we commonly see drivers with 25 or possible 30% efficiency. For example, the JBL 2445J has a midband efficiency of 30%, while the 2425H/J design has a midband efficiency of 25%. The shortfall in efficiency is for the most part quite negligible, and it is largely due to eddy current losses in the top plate and pole piece of the driver.

Figure 2 shows the electrical equivalent circuit of a compression driver operating in its midband range. Maximum efficiency occurs when the value of radiation resistance, R_{ET}, is made equal to the voice coil resistance, R_E. The significance of radiation resistance is that it is the useful acoustical load reflected back into the electrical part of the system, representing a resistive load on the power amplifier in series with the voice coil resistance. See Appendix I for calculations of radiation resistance and efficiency.

Figure 2: **Equivalent Electrical Circuit, as seen at Terminals, of a Compression Driver at Mid-Frequencies**



4. High-Frequency Response:

A. Mass Break-point:

All high-frequency drivers begin a roll-off in their output above what is called the mass break-point frequency. Obviously, the mass of the larger diaphragm assemblies is greater than that of the smaller devices, as is its voice coil resistance. However, the larger magnet structure and the increased length of wire in the voice coil provide more driving force, and this enables the larger driver to maintain its mass break-point substantially in the same frequency range as the smaller driver.

For most drivers intended for high quality sound or music reinforcement, the mass break-point is in the 3500 Hz range. Above that frequency, the response falls off at 6 dB/octave. In many applications, the fall-off can be ignored, since it may correspond, more or less, to accepted system equalization practice. But in the cases of studio monitoring and music reinforcement, the inherent roll-off of the driver will have to be compensated for. JBL's most recent passive dividing network designs have provision for such compensation. Inasmuch as the high-frequency portion of a system is always padded down relative to the low-frequency portion, there is power to spare, thus allowing the compensation to be made without additional power input.

Figure 3 shows the equivalent circuit of the driver at high frequencies. Note that there are three reactive elements in the circuit. The most important of these three is the shunt capacitance, which governs the mass break-point. The element L_E is the inductance of the voice coil, and it can result in another high-frequency break point in response. In JBL's drivers, an electrical "shorted turn" is plated directly onto the pole piece, and this effectively nulls out the voice coil inductance. The circuit element labeled L_{CEC} is proportional to the volume of air between the diaphragm and the phasing plug. If this spacing is too large, then there will be another break point in the frequency response. Typically, in most driver designs, this

Figure 3: **Equivalent Electrical Circuit, as seen at Terminals, of a Compression Driver at High-Frequencies**

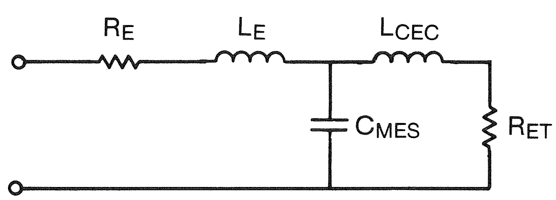
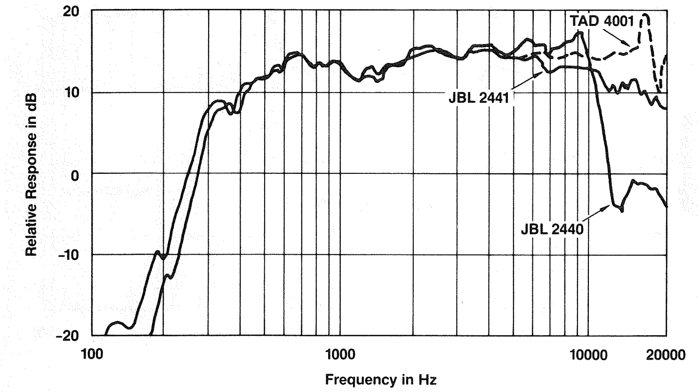


Figure 4: **On-Axis Response of JBL 2440, 2441 and TAD 4001 Drivers on a JBL 2350 Horn**



additional break-point is quite far out in frequency and is of no consequence.

B. Secondary Resonances:

Our neat theoretical model does little to explain the role of secondary resonances. These are controlled break-up modes of the diaphragm and surround structure which can be used to shape high frequency response in a beneficial way. Figure 4 shows the response of three 100 mm diaphragm drivers mounted on the same horn, a JBL 2350. The old JBL 2440 driver went out to about 9 kHz without showing any apparent mass break point. The reason for this was the role of a secondary resonance in the surround which kept the response rising. Recall that the 2440 had an aluminum diaphragm with a half-roll surround. The TAD 4001 driver has basically the same kind of surround treatment, but its beryllium material, because of its increased stiffness, exhibits the same characteristic moved out about an octave. The JBL 2441 driver, with its unique surround treatment, controls secondary resonances in a different way, producing an extended peak-free, but slightly rolled off, response. For further discussion please see the reference at the end of this Technical Note.

5. Measurement and Specification of Compression Drivers:

In order to eliminate the variable loading effects of horns, compression drivers are usually measured, for the sake of comparisons, on a device known as a plane wave tube (PWT). An example is shown in Figure 5. The tube is cylindrical, with a measurement microphone placed close to the end where the driver is attached. Progressively, as sound is propagated down the tube, it encounters a carefully tapered acoustical resistance wedge. The sound has

Figure 5: **Details of a Plane Wave Tube**

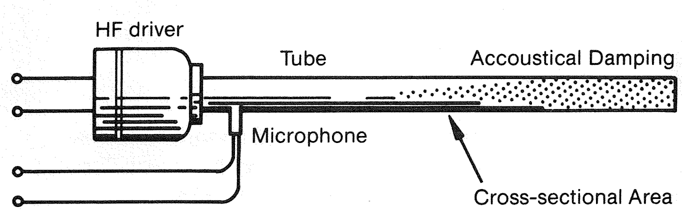
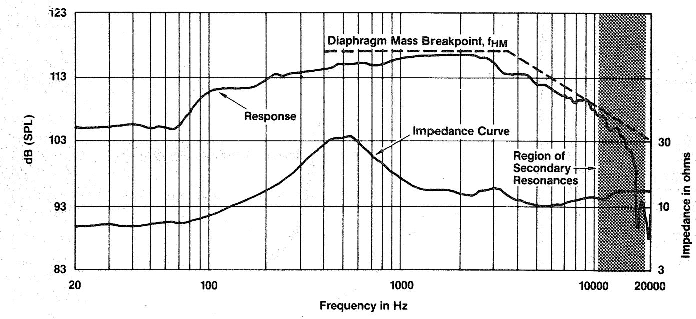


Figure 6: **Response of JBL 2425 Driver on 25.4mm (1 in) PWT with 1 Milliwatt Input**



been effectively attenuated by the time it reaches the end of the tube, and there is no reflection back toward the driver. The loading of the tube on the driver is thus quite smooth over a relatively wide frequency range.

A typical PWT curve is shown in Figure 6 for a JBL 2425 driver. Note the location of the mass break point.

When comparing data from different manufacturers, be careful in noting the diameter of the PWT used for the measurements. All JBL drivers are referred to a diameter of 25.4 mm, even if the actual measurement was made on a PWT of different diameter. Some manufacturers use a PWT with a diameter of 19 mm. This smaller diameter produces a level which is 2.5 dB greater than on a 25.4 mm tube, and that difference should be noted.

See Appendix III for sample calculations involving plane wave tubes.

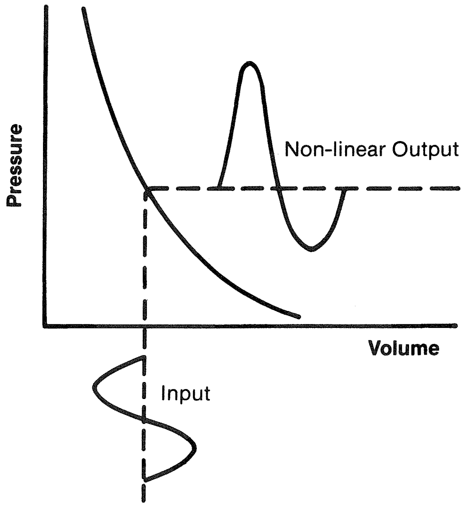
6. Non-Linearities in Compression Drivers:

High frequency distortion in compression drivers is basically a thermodynamic phenomenon. It results from the existance of high acoustical pressures at the diaphragm-phasing plug interface rather than from mechanical non-linearities in the moving system itself. It usually comes as a surprise to many sound contractors to find out just how little displacement there is in a compression driver operating under normal conditions.

Referring to Frank Massa's Acoustical Design Charts (Blakiston Company, Philadelphia, 1942), we calculate from chart 78 that a JBL 2445J driver, with 10 acoustic watts output at 1 kHz, will produce a peak diaphragm displacement of 0.2 mm, or 0.4 mm peak to peak. For each doubling of frequency, the displacement will drop in half, so it can be seen that normal usage results in quite small excursions of diaphragms in compression drivers. Over such small ranges of motion, the moving system itself is quite linear; that is, displacement is a direct function of the driving force. For normal acoustical outputs in the one to five watt range, it is clear that excursions are indeed quite small.

Figure 7 shows the basis non-linearity of the volume-pressure relationship in gasses. At the bottom of the graph, we represent a linear, sinusoidal driving function as produced by the diaphragm. The pressure produced by this is non-linear for large changes in volume. In a horn-driver combination, such high pressures develop even

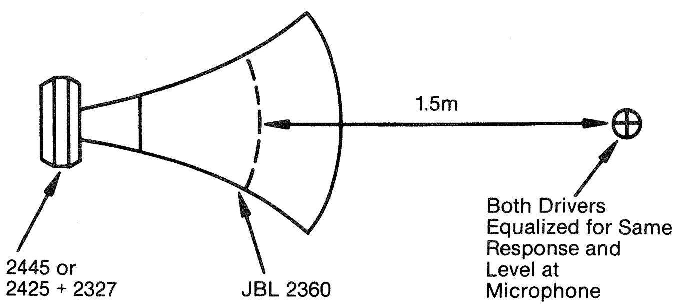
Figure 7: **Non-Linear Relationship Between Volume and Pressure in a Gas**



greater distortion as the wave propagates down the horn. The more rapidly the horn flares outward, the lower the pressures become, and the lower the distortion will be.

In order to compare high-frequency drivers, it is necessary to mount them both on the same horn, drive them to the same output level, and measure them at the same distance. If necessary, their frequency response curves may be equalized differently for their outputs to track at high frequencies. Using the test set-up shown in Figure 8, we compared the second and third harmonic distortion components of a JBL 2445/2360 combination and a JBL 2425/2327/2360 combination.

Figure 8: **Test Set-up for Driver Comparison**



Both horn/driver combinations were driven to the same output level and were equalized with a 6 dB/ocatve boost above 3 kHz in order to maintain flat power response and flat axial response on the 2360 horn. The results of these measurements are shown in Figures 9 and 10. Distortion components in the graphs are raised 20 dB. In the graph of Figure 9A, we observe that the value of second harmonic distortion at 10 kHz is some 12 dB below the fundamental, and this corresponds to a distortion of 25%. In the graph of 10A, the second harmonic distortion at 10 kHz is some 8 dB below the fundamental, corresponding to 40% distortion.

In Appendix IV, we present calculations of distortion. Note that the calculated values are in good agreement with the measured values.

Figure 9A: **2445J and 2360. Distortion raised 20 dB. 6.3 Volts at 1 kHz**

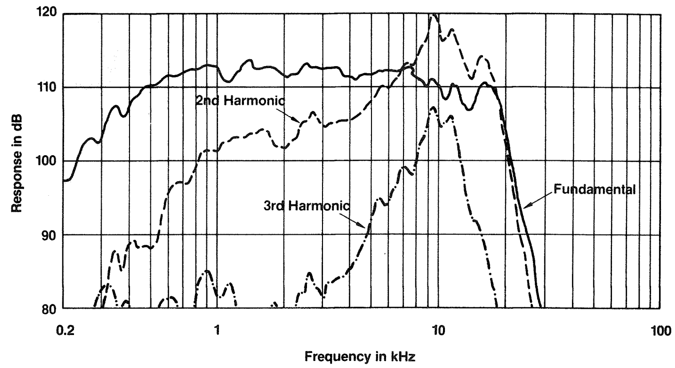
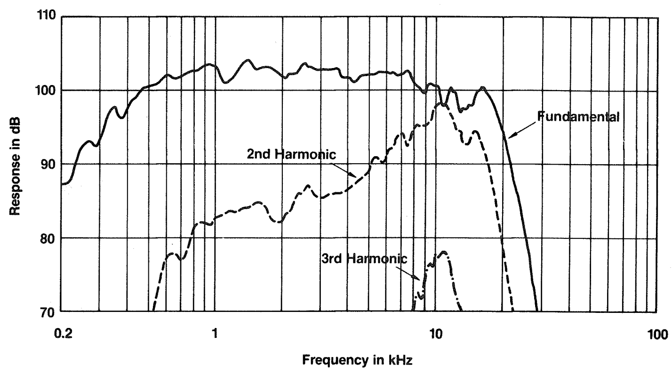


Figure 9B: **2445J and 2360. Distortion raised 20 dB. 2 Volts at 1 kHz**



The drive levels used in these measurements are typical of horn/driver combinations which have been equalized for flat power response. Second harmonic components rise fairly gradually and are apparent throughout the midband. For a given intensity, second harmonic distortion doubles with each doubling of driving frequency.

Third harmonic components become quite apparent at higher drive levels, and they are most pronounced in the range above 5 kHz. For a given intensity, third harmonic distortion rises as the square of the driving frequency.

We do not hear the harmonics of high frequencies, but the same non-linearities which give rise to second and third harmonics will also cause intermodulation distortion of frequency combinations in midband, and these will be quite audible.

JBL does not manufacture an intermediate size 75 mm (3 in) diaphragm driver, but it should take only a little extension of the theory verified here to show that the intermediate design would exhibit harmoinc distortion at some point between that of the large and small drivers.

7. Summary:

A. No compression driver can be more than 50% efficient in the range below its mass break-point. Typical good drivers are usually no greater than 30%.

Figure 10A: **2425J and 2327/2366. Distortion raised 20 dB. 6.4 Volts at 1 kHz**

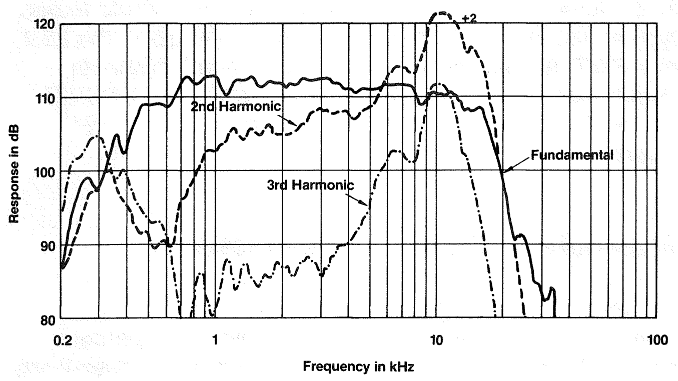
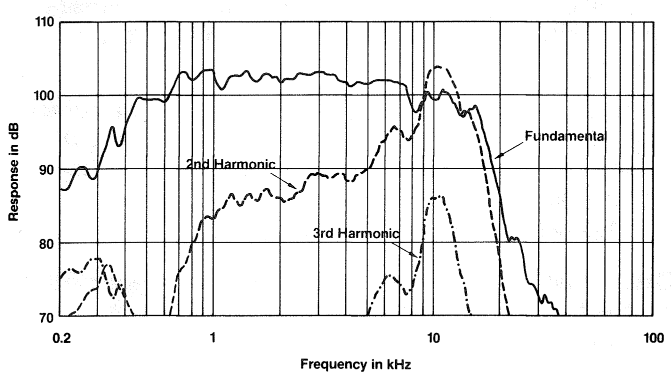


Figure 10B: **2425J and 2327/2360. Distortion raised 20 dB. 2.05 Volts at 1 kHz**



B. All high frequency drivers will begin a roll-off in power output above about 3500 Hz. Allowance must be made for this in system equalization when Bi-Radial horns are used. Recent modifications in JBL's passive networks provide the required high-frequency boost to correct the driver's power response.

C. For comparisons between competitive drivers, PWT data must be carefully noted. A standard reference diameter is 25.4 mm (1 in), and the following chart relates mid-band PWT sensitivities, with one milliwatt input, to the corresponding efficiencies:

120 dB-SPL	50% efficient
119 dB-SPL	40%
118 dB-SPL	30%
117 dB-SPL	25%

D. Diaphragm diameter of high-frequency drivers has little to do *per se* with extended high frequency response. Choice of diaphragm material and surround treatment are the significant factors controlling response beyond 8-10 kHz.

Such drivers as the JBL 2482 have been optimized for high power handling in the speech range with limited high frequency output above the mass break point.

E. Field comparisons between drivers should be made on the same horn with the input signal adjusted (and equalized, if need be) for the same response as measured at the horn's output.

F. Distortion in high frequency drivers is largely a function of acoustical output, not electrical input. The advantage of a large driver over a smaller one is reduced harmonic distortion for the same acoustical output.

8. Conclusions:

For years, many users of JBL products have specified the larger compression driver over the smaller designs simply on the basis that they sounded better. We have shown some of the reasons why this is true, and we emphasize again that for applications where naturalness of sound is important, the 2445J driver should be the one of choice—unless it can be demonstrated that there are compelling budget limitations.

Appendix I: Calculation of Theoretical Efficiency:

Radiation resistance, R_{ET}, is defined as follows:

$$R_{ET} = S_T (Bl)^2 / \rho_0 c S_D^2$$

where $\rho_0 c$ is the acoustical impedance of air, 415 N · sec/m.

Efficiency is given by the equation:

$$\text{Eff (\%)} = 2\, R_E\, R_{ET} / (R_E + R_{ET})^2 \times 100$$

We will now calculate R_{ET} for the JBL 2445J driver:

S_T = .0008 m^2
Bl = 18 newton/ampere
S_D = .008 m^2
R_{ET} = (.0008) $(18)^2$ / (415) $(.008)^2$
R_{ET} = .259/.02656 = **9.8 ohms**

R_E for the 2445J driver is 8.5 ohms, and the sum of these is very close to the 16 ohm rated impedance of the driver.

Calculating the efficiency:

$$\text{Eff (\%)} = 2(8.5)\,(9.8) / (8.5 + 9.8)^2 \times 100$$

Eff (%) = **49.7%** (see note in text)

Appendix II: Calculation of High-frequency Break-point:

The mass break-point frequency, f_{HM}, is given by the equation:

$$f_{HM} = (Bl)^2 / \pi\, R_E\, M_{MS}$$

We can calculate the value of f_{HM} for the JBL 2445 driver by taking the pertinent quantities and entering them into the above equation:

Bl = 18 Tesla
R = 8.5 ohms
M = .00346 kilograms
$f_{HM} = (18)^2 / \pi\, (8.5)\, (.00346)$ = **3507 Hz**

Appendix III: Plane Wave Tube Calculations:

The sound pressure in the tube measured by the microphone is given by:

$$\text{Pressure} = \sqrt{\text{Power } (\rho_0 c) / \text{Area}},$$

where power is in watts and cross-sectional area is in square meters.

The pressure given by this equation will be in pascals. In order to convert it to dB-SPL, we use the following equation, noting that one pascal represents a level of 94 dB-SPL:

$$\text{SPL} = 94 + 20 \log \sqrt{\text{Power } (\rho_0 c) / \text{Area}}$$

Let us take a PWT which is 25.4 mm (1 in) in diameter and introduce into it an acoustical power of one watt. We then have:

$$\text{SPL} = 94 + 20 \log \sqrt{(1)415/.0005}$$

SPL = 153 dB-SPL

Let us assume that we are exciting an ideal driver with one watt. Then, because it is only 50% efficient, there should be only 0.5 watt available into the tube, and we would read 150 dB-SPL, (153 – 3 = 150). For a JBL 2445 driver with an efficiency of 30%, we would read about 148 dB-SPL.

In order to produce more moderate levels in the PWT, it is customary to use an input power of one milliwatt, some 30 dB lower in level than one watt. Thus, we would expect typical JBL drivers to produce levels of 118 dB in the 25.4 mm PWT. A quick survey of JBL specification sheets shows that typical PWT one milliwatt ratings are 118 dB for the 2441J and 2445J drivers and 117 dB for the 2425J driver.

Appendix IV: Distortion Calculations:

Beranek (Acoustics, McGraw-Hill, New York, 1954) presents the following equation for determing percent second harmonic distortion in a compression driver-horn combination:

$$\text{\% Second Harmonic} = 1.73\, f/f_C \sqrt{I_T} \times 10^{-2}$$

In this equation, f represents the driving frequency, f_C the nominal cut-off frequency of the horn, and I_T represents the intensity (acoustic watts per square meter) at the phasing plug-diaphragm interface.

Taking the measurements shown at Figure 9A, we observe that a drive of 6.3 volts was applied at 1 kHz. Taking the nominal impedance of 16 ohms, we calculate the electrical power input as:

$$\text{Power in} = (6.3)^2 / 16 = 2.5 \text{ watts}$$

Calculating the acoustical power at the throat, we multiply the electrical power input by the efficiency of 30%.:

$$\text{Acoustical power} = (2.5)\,(.3) = 0.75 \text{ watts}$$

The intensity, I_T, is acoustical power divided by S_T:

$$I_T = (.75)/.0008 = 0.94 \times 10^3 \text{ watts/m}^2$$

We will assume that the effective cutoff frequency of the horn and throat is 200 Hz, and we now calculate the distortion at 10 kHz:

$$\text{\% 2nd} = (1.76)\,(10000/200) \sqrt{9.4 \times 10^2} \times 10^{-2}$$

% 2nd = 26%

For the 2425J driver, we use the following values:

Applied potential = 6.4 volts
Impedance = 16 ohms
S_T = .0002 m^2
Efficiency = 25%

Using the same cutoff frequency, we calculate a value of **48%** 2nd harmonic distortion at 10 kHz.

Reference:

F. Murray and H. Durbin, "Three-Dimensional Diaphragm Suspensions for Compression Drivers," Journal of the Audio Engineering Society Vol. 28, No. 10, pp. 720-725 (October 1980)

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