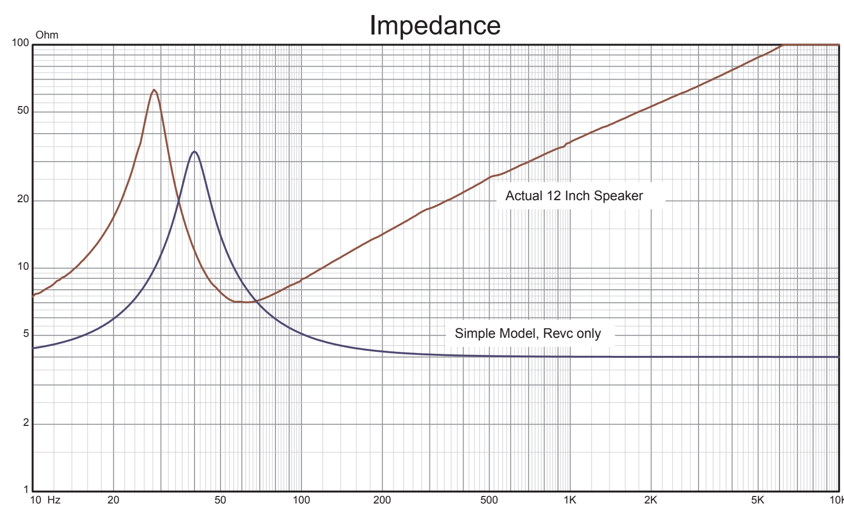
4.11 Motor Impedance

All electrodynamic transducers contain a magnetic motor structure comprised of iron and other conductive materials. These are typically the top plate, back plate, and center pole piece. The materials combine to form a highly complex impedance network which is strongly frequency dependent. Accurate modeling of this *motor* impedance at mid- high frequencies is significantly complex.

The previous circuit model only included a single electrical system element *Revc*. This is a simple fixed resistor with a constant value at all frequencies. The graph below shows two transducer impedance curves; the previous simple model of the example transducer, and the measured impedance of an actual 12 Inch woofer.

At frequencies above 100Hz the simple model returns to a flat line value of 4 Ohms. However, the actual transducer shows a dramatic impedance rise with increasing frequency. Clearly the single Revc element of the simple model is incapable of representing realistic motor impedance.

The impedance increase has a direct result on the acoustic output from the transducer. Since electrodynamic transducers generate mechanical force from the electrical current, the rising impedance will cause a similar decrease in the voice coil current. As such there is less mechanical driving force available, and therefore less acoustic output.



The rising impedance of the actual transducer has the obvious appearance of inductance. It would seem that adding an additional inductor component *Levc* would be a logical approach. The electrical circuit for a free field transducer is now shown below with the additional component *Levc*. The relationships for the mechanical components are also shown in the equations to the left.

The graph below again shows the response of the measured impedance for the 12 Inch woofer, and also the equivalent model impedance of the circuit with an *Levc* value of 5.5mH. While the impedance of the model also rises now at high frequencies, it is a very poor fit.

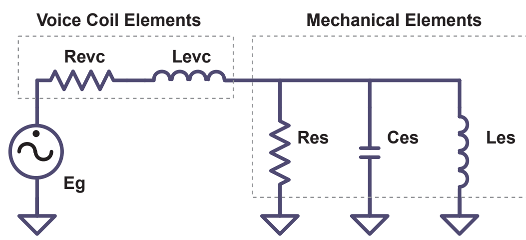
No matter what value is chosen for *Levc,* the curves will never match. Note that the *slope* of the impedance rise is not the same. This is also indicated in the phase response, where the actual curve reaches 60 degrees and the model overshoots this to 90 degrees. Note also that some of the worst error occurs even at very low frequencies near 100Hz.

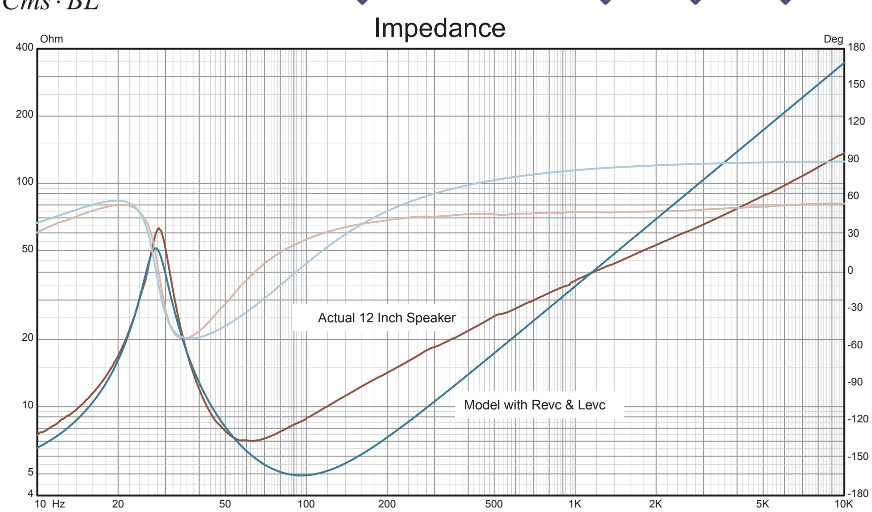
$$Ze = \left(\frac{BL}{Sd}\right)^2 \cdot \frac{1}{Za}$$

$$Res = \left(\frac{BL}{Sd}\right)^2 \cdot \frac{1}{Ras} = \frac{BL^2}{Rms}$$

$$Ces = \left(\frac{Sd}{BL}\right)^2 \cdot Mas = \frac{Mms}{BL^2}$$

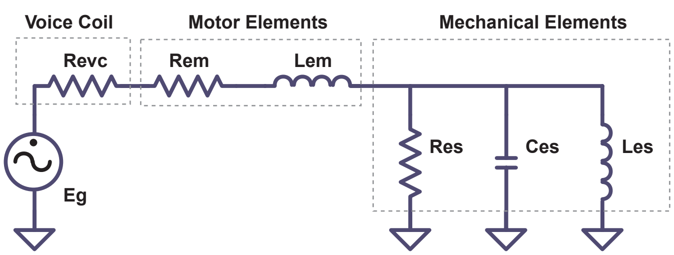
$$Les = \left(\frac{BL}{Sd}\right)^2 \cdot Cas = Cms \cdot BL^2$$





The previous model using *Levc* corresponds to the **STD** model in *EnclosureShop,* and is the old traditional method for transducer modeling. This model produces an error of nearly 6dB at 100Hz.

To improve the simulation of the transducer impedance, a more sophisticated method must be developed to describe the motor impedance. In the previous graph it was noted that the phase only achieves a maximum of about 60 degrees, rather than the nearly inductive 90 degrees of the model. This can only be the result from a substantial increase in *resistance*. Therefore, an additional element must be defined to incorporate more resistance into the motor impedance.



The circuit here shows a new arrangement for the electrical circuit, and two new components: *Rem* and *Lem*. These two comprise the *motor impedance*. Both are frequency dependent.

Revc remains a fixed quantity that represents the pure voice coil resistance as measured at DC (0Hz).

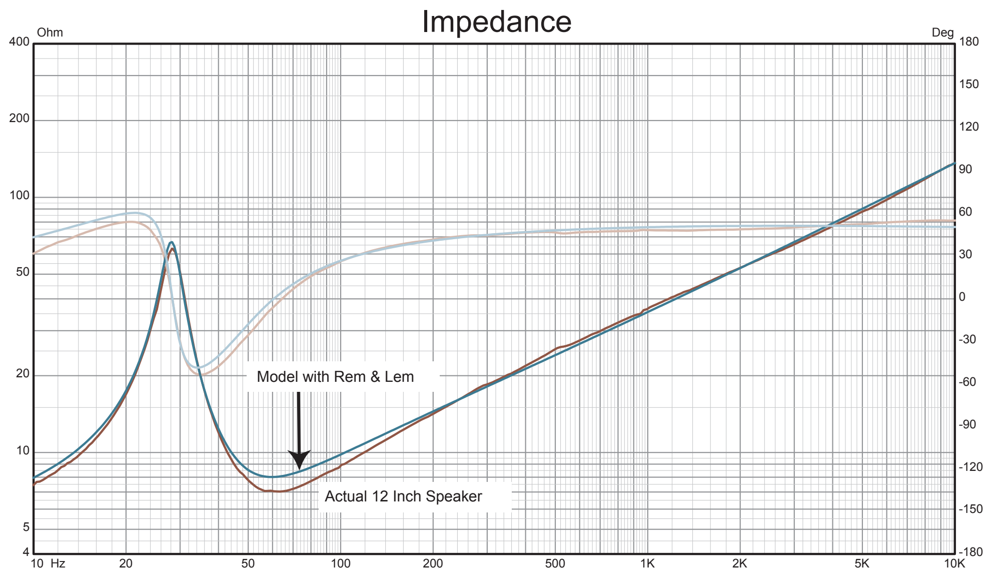
The question now at hand is how to define suitable functions for *Rem* and *Lem*. Looking at the previous graph it is noted that the slope of the impedance rise is much less then what the *Levc* model could produce. Yet the slope is nearly log-linear.

With this observation we can define some simple functions which allow for this capability as shown below. These functions permit the log slope to be adjusted for both the resistance and reactance individually.

The four function coefficients *Krm*, *Kxm*, *Erm*, and *Exm* can be calculated easily from the measured impedance data by using both the magnitude and phase of two points anywhere in the mid-high frequency region. With these four values and the equations below, the actual component values for *Rem* and *Lem* can be found at any frequency. While the coefficients are fixed constants, the *Rem* and *Lem* values themselves will change with frequency.

$$Rem = Krm \cdot \omega^{Erm}$$

$$Xem = Kxm \cdot \omega^{Exm} \qquad Lem = Kxm \cdot \omega^{Exm-1}$$



The graph above now shows the results using the new motor impedance model. There is substantial improvement. Both the magnitude and phase match very well across the entire three decades of frequency. The maximum error of 1.1dB occurs near 60Hz. The four coefficient values used are:

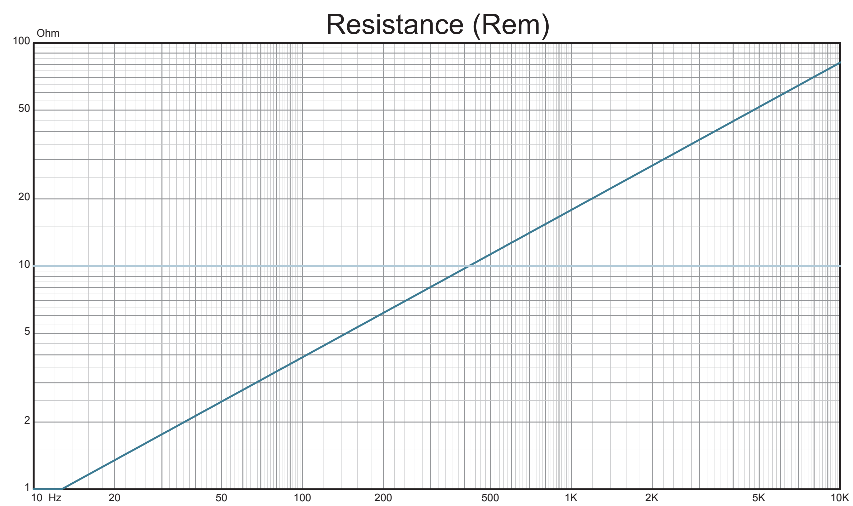
Krm	= 55.5m Ohm	Erm	= 0.66
Kxm	= 175.0m Henry	Exm	= 0.58

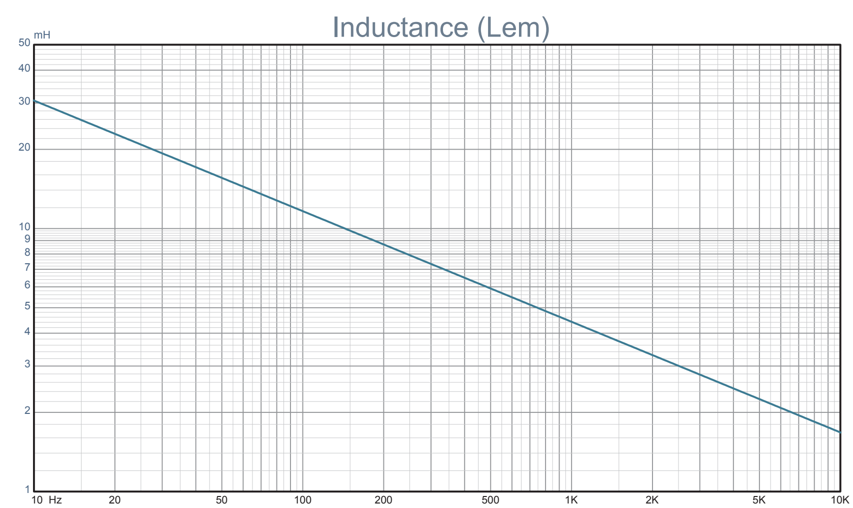
The *Rem* and *Lem* functions are graphed on the next page. The resistance increases with frequency while the inductance decreases. These are typical results for iron based magnetic systems. They reflect the losses and magnetic permeability changes across frequency.

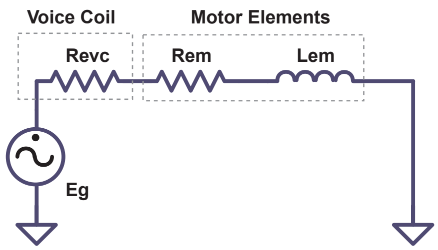
Note that the resistance *Rem* varies from approximately 1 Ohm to 100 Ohms between 10Hz and 10kHz. Also that the inductance *Lem* declines from 30mH at 10Hz to 1.7mH at 10kHz. These are not trivial changes.

This motor impedance modeling approach corresponds to the **TSL** model utilized by *EnclosureShop*. The *Transducer Model Derivation* dialog utilizes an optimization technique to determine the four coefficients based on a best fit to the measured data across the entire frequency range.

Compare this method to the previous conventional STD model. To give an equivalent fixed *Levc* value in light of the *Lem* curve data presents a clear problem. A single fixed inductance cannot possibly represent this function adequately. The general method is to quote the value at 1kHz, but it should be understood that this approach is an extremely crude approximation, and in reality is virtually meaningless. It also fails to account for the important contribution of *Rem* altogether.







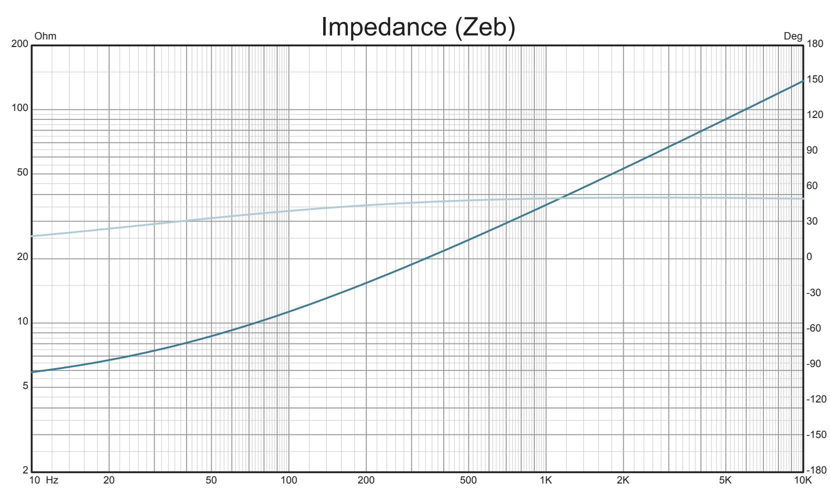
Blocked Impedance

All of the previous impedance curves included both the mechanical and electrical portions of the circuit. However, another useful technique is to isolate the electrical impedance by itself. If the diaphragm is held motionless while being driven, the compliance goes to zero, and along with it the electrical circuit value of *Les*. This effectively shorts out the mechanical elements leaving only the electrical portion. This is known as the *blocked* impedance and is shown here in the schematic.

One way of blocking a transducer is to remove or cut a hole in the dust cap, and glue the inside of the former to the center pole piece with epoxy. *Note: the transducer will no longer be usable.*

While it may be somewhat possible to block a transducer by some sort of clamping, eliminating all motion at all frequencies is extremely difficult. Such is the need for the epoxy method. Even when using epoxy one may still hear a small amount of high frequency sound during a sweep. Other parts of the voice coil can still flex under the strong magnetic field.

The graph below shows the blocked impedance of the transducer. Note that there is substantial increase over *Revc* (4.7 Ohms) even at very low frequencies.



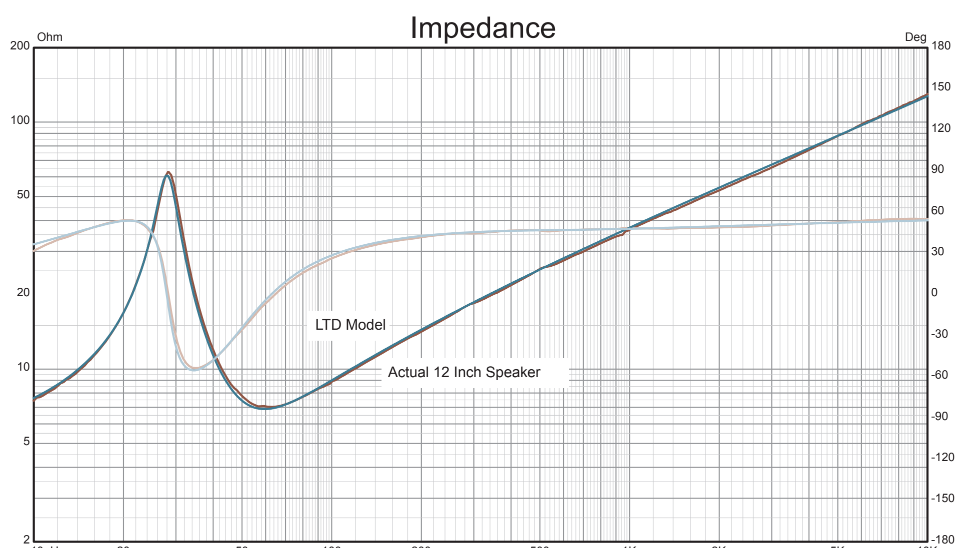
The previous TSL model was a considerable improvement over the conventional STD model. However, there was still significant error remaining in the low frequency region near 60Hz. This outcome is often seen in many transducers. If the simulation accuracy is to be improved further, additional advancements must be made to the *Rem* and *Lem functions*.

While the shape of the mid-high frequency impedance curve is nearly log-linear, there is some curvature. Actual measurements of many different transducers have shown a noticeable break-point and slope change across frequency. One way to improve the motor impedance model is to provide for dual slopes with a transition frequency between them. This is the method employed in the **LTD** model used by *EnclosureShop*.

$$Rem = Rem_{LTD}(\omega, Ve, Ta) \quad ; \quad (Krm, Frm, Drm, Erm, Vrm, Trm)$$

$$Xem = Xem_{LTD}(\omega, Ve, Ta) \quad ; \quad (Kxm, Fxm, Dxm, Exm, Vxm, Txm)$$

The graph below shows the comparison of the measured data and the LTD model simulation. The curves are nearly identical, with a difference of only a fraction of a dB at any frequency. The advanced LTD motor impedance model utilizes 12 parameters. It also incorporates the ability to simulate motor impedance variations due to changes in temperature and drive level. The *Transducer Model Derivation* dialog employs optimization to determine the parameters for a best fit solution.



Since the acoustic response is very much dependent on the impedance response, the improvements in the motor impedance model should facilitate similar improvements for the simulation of acoustic response.

To compare the performance of the various models against actual measurements, the 12 Inch woofer was mounted in a 36 Liter sealed enclosure, and recessed in a very large plane to approximate an infinite baffle. The graphs on the following pages show the comparisons for each model.

It should be noted that the diaphragm breakup effects at higher frequencies can also be represented using additional features in the *EnclosureShop* transducer models. This will be discussed in the following sections. However, the focus here is to compare the performance between 10Hz - 400Hz (*ka<1*).

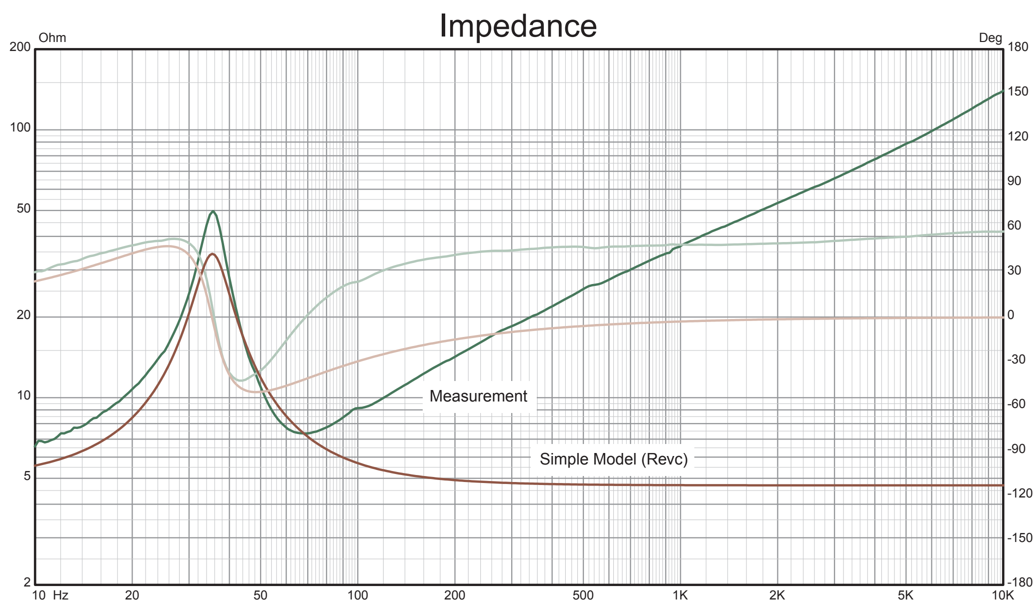
• **Simple Model (Revc) [Highpass Approximation] Comparison**
The simple model is merely a degenerated form of the STD model by using a zero value for *Levc*. This model is also well known as the common Highpass filter approximation. As shown previously the impedance fails to replicate any part of the real transducer behavior, with the exception of the basic mechanical resonance hump. The SPL response shows substantial differences as well, with errors of 10dB beginning at 200Hz. Surprisingly, even at very low frequencies of 10-30Hz there are noticeable differences in the response of nearly 5dB.

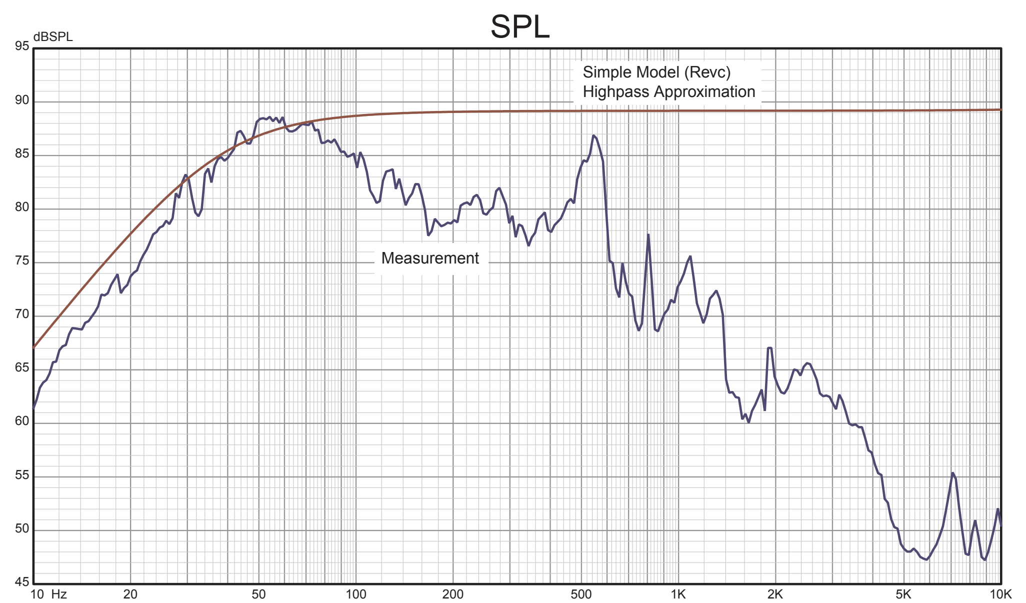
• **Standard STD Model (Revc, Levc) Comparison**
The standard STD model adds a fixed *Levc*. The impedance curve now has a rising impedance, but it does not replicate the measurement. The worst error occurs near 100-200Hz. The SPL response now decreases due to Levc, but again the shape does not match that of the actual measurement. As with the impedance curve, some of the worst error occurs in the range of 100-200Hz. Also, the differences at very low frequencies have not been improved.

• **LEAP-4 TSL Model Comparison**
By use of the *Rem*, *Lem* motor impedance model there is dramatically superior replication of the impedance measurement. Likewise the SPL response curve is also greatly improved, both in the 80-300Hz and 10-30Hz regions.

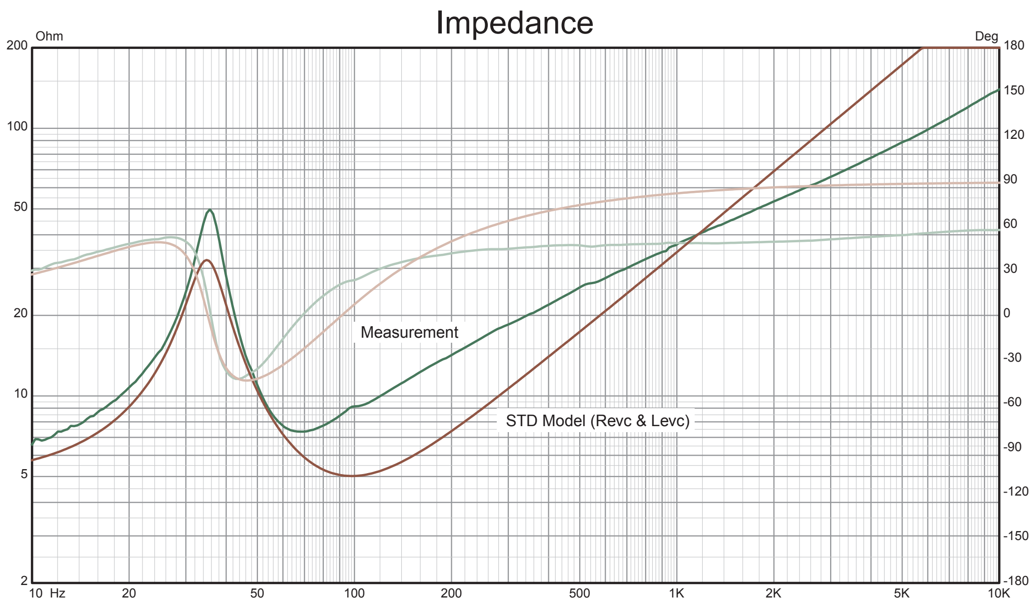
• **LEAP-5 LTD Model Comparison**
The additional motor modeling improvements here produce an impedance curve virtually identical to the measurement everywhere. The SPL response also shows significant improvement across the entire 10-200Hz region.

• Simple Model (Revc) [Highpass Approximation] Comparison

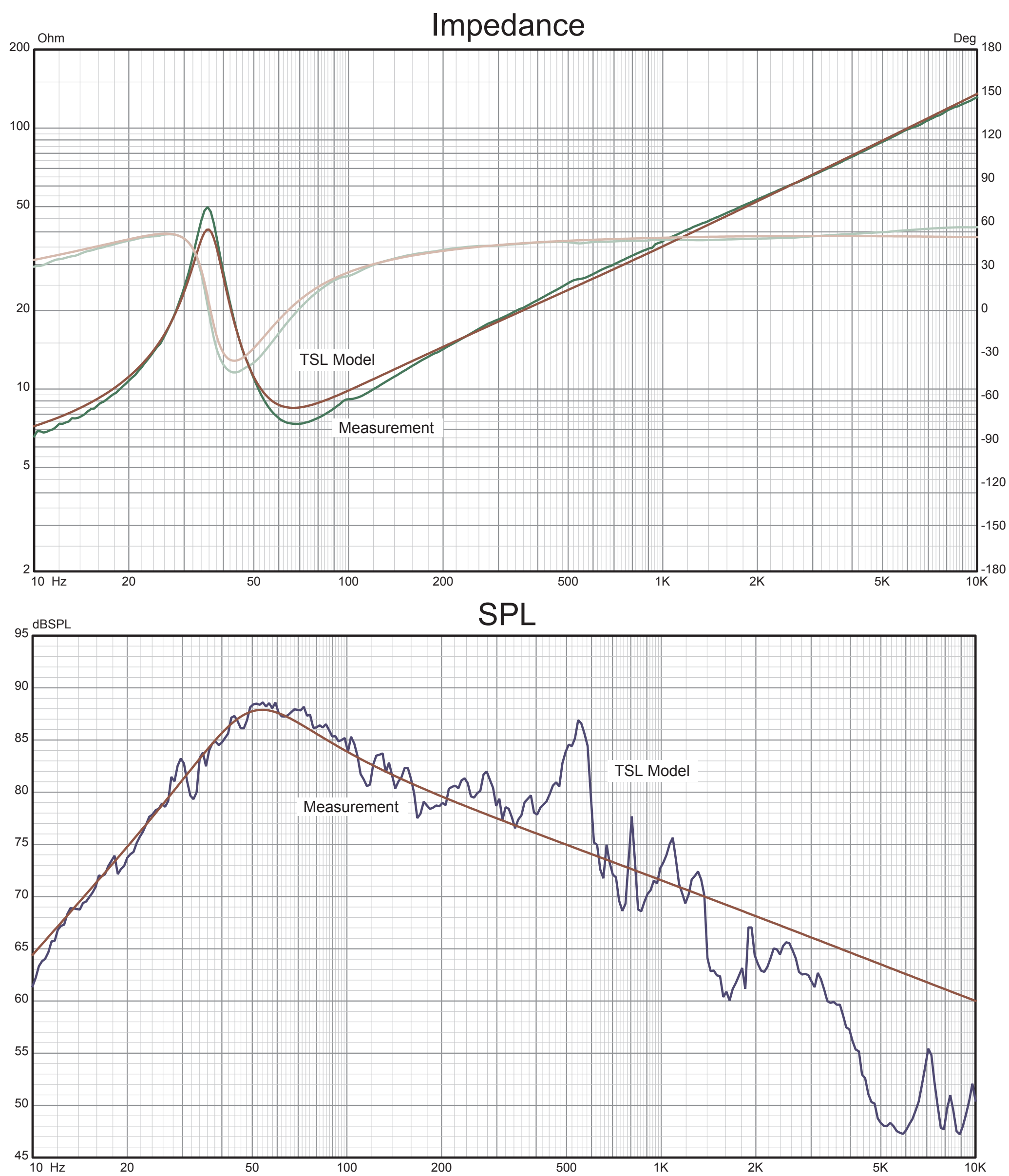




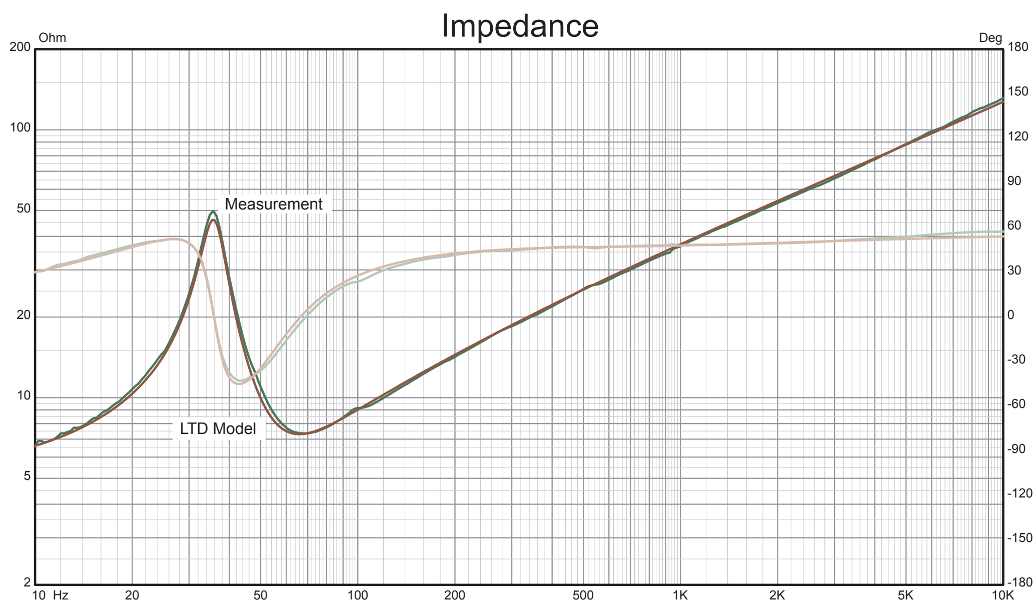
• Standard STD Model (Revc,Levc) Comparison

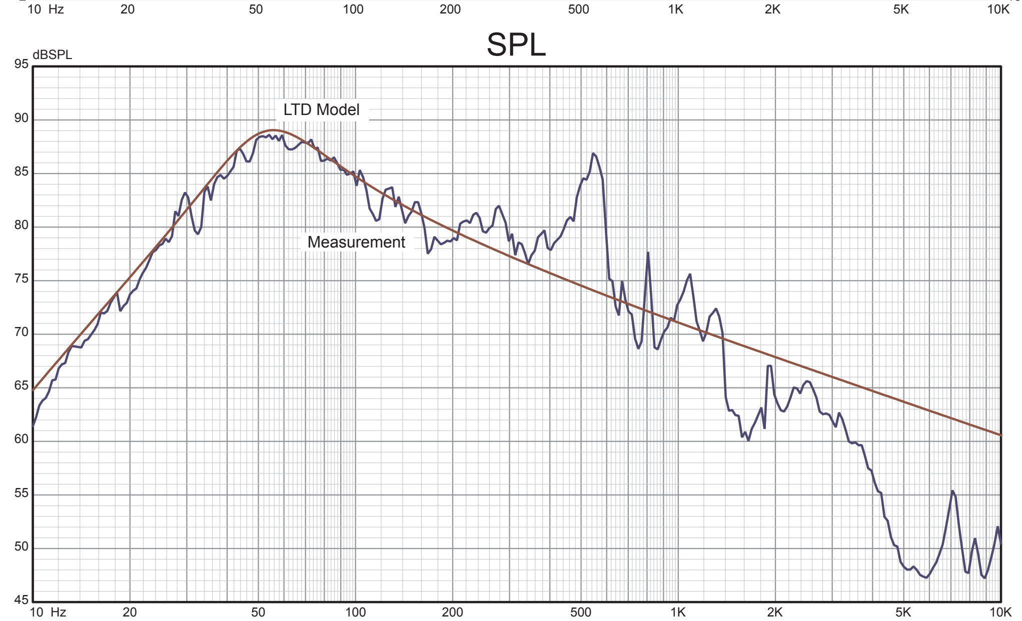


• LEAP-4 TSL Model Comparison



• **LEAP-5 LTD Model Comparison**



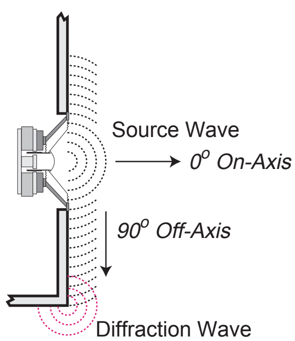


4.12 Diaphragm Structure

The structure of a transducer diaphragm controls the essential high frequency (*ka>1*) directional characteristics. The primary structural parameter is the diaphragm *shape*. Most transducers contain circular diaphragms, but some have also been produced with square, triangular, and hexagon shapes. Ribbon tweeters are an example of a rectangular diaphragm with high aspect ratio.

Probably the next most important criteria is the *profile* of the diaphragm. Low frequency transducers often have a recessed profile resembling a truncated cone. High frequency transducers often have a dome profile. Some may also have a flat profile such as in the case of ribbon devices.

These two parameters *Shape* and *Profile* are used by the transducer models of *EnclosureShop* to determine the essential high frequency characteristics for the transducer. They directly control radiation impedance, directivity, and off-axis response for the transducer.



These parameters greatly affect the diffraction modeling of enclosures. For transducers which are surface mounted, the sound wave radiating towards the edge of the enclosure results from the 90 degree off-axis radiation of the transducer as shown here in the pictorial.

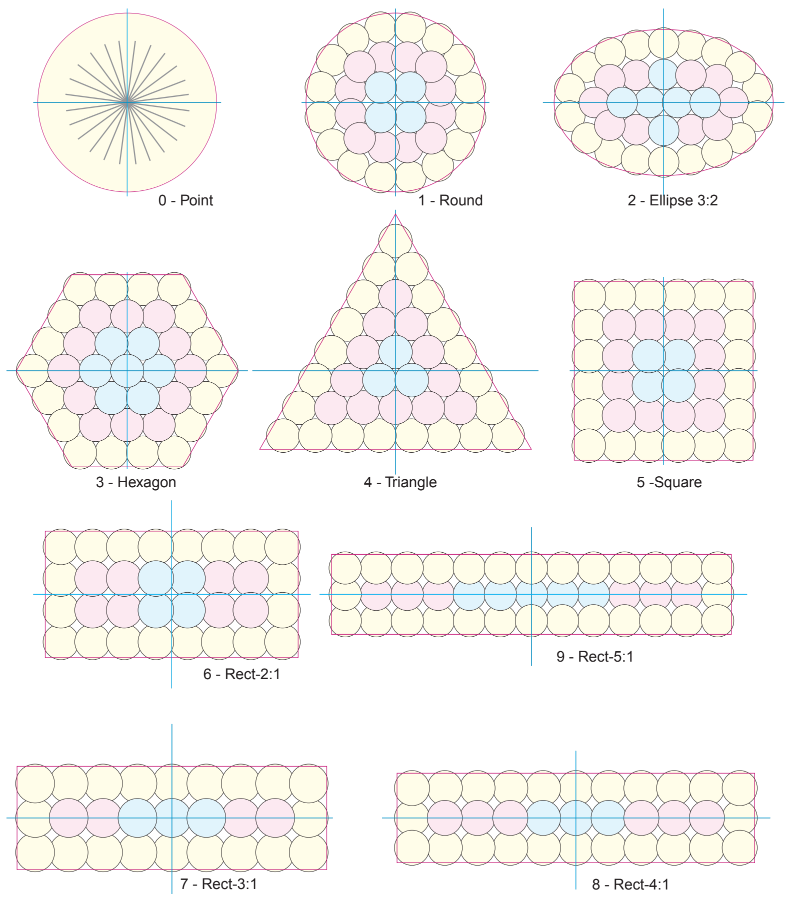
All of the acoustic pressure diffracting around an enclosure has its origin in the 90 degree off-axis response of the transducer. Errors in the simulated off-axis behavior can produce errors in the entire simulated field around an enclosure. This is especially significant for the response at the sides and rear of an enclosure, where all sound arrives solely from diffraction. Therefore, realistic diffraction analysis demands that realistic models be utilized for the directional behavior of the transducers.

The directional behavior of any specific transducer is entirely unique. It is very much like that of a human fingerprint. No two are alike, and the off-axis simulations provided by *EnclosureShop* will never perfectly match any particular transducer. However the fundamental directional behavior of the transducer relative to its shape and profile can be simulated very effectively.

The directional models used by *EnclosureShop* were developed through extensive measurements on many different transducers, and represent an average behavior for devices of similar shape and profile.

In order to simulate the behavior of all possible structural variations in a generalized fashion, a methodology of *small source arrays* was developed. The small sources embody their own directional characteristics. Additional transfer functions are also applied to the array elements which enable a wide variety of directional characteristics to be emulated.

Each transducer is modeled by a group of sources arranged in the required geometry as shown in the drawing below. Between two and three dozen array elements are used in each shape model. These sources are driven by a suitable group of transfer functions as dictated by the shape and profile parameters. The pseudo *Point* source model is a special shape with no directionality.



Diaphragm Shapes