Enhancing loudspeaker efficiency and *Bl(x)* symmetry with *Virtual Voice Coil* (original manuscript sent to VOICE COIL editor)

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Virtual Voice Coil (*VVC*) is the ideal software for designing voice coil and predicting audio transducer parameters with the maximum accuracy in an easy way. One of the keys that allow the accuracy of *VVC* prediction is given by a complete temperature management involved in loudspeaker calculus. For a precise calculus of loudspeaker parameters and over all the sound pressure prediction in the far field, based on a linear model and assuming a radiation in a half space (2pi-sr free field), it is necessary to recognize temperatures interactions among the terms of the reference efficiency formula of electro-acoustical conversion

$$\eta_0 = \frac{\rho_0}{2\pi\ c} + \frac{Bl^2}{R_e} + \frac{{S_d}^2}{{M_{ms}}^2}$$

In the first term there is the ratio between density of air ρ_0 and speed of sound c. The second term there is the ratio between force factor Bl (considering Bl at coil rest position *x= 0*) and DC resistance R_e, then we can find the effective radiation area S_d and moving mass M_{ms}.

In reality, there are 3 kind of temperatures for defining loudspeaker efficiency and thus the reference sensitivity in the loudspeaker pass band.

The 1st temperature is linked to voice coil winding and in *VVC* it is called w*ire temperature* (*wTemp*). It represents the environment temperature at which the voice coil is assembled. In other words, it is the temperature of the supplier factory during voice coil winding phase. By the wire temperature *VVC* defines primary electrical resistance included in R_e, moreover the materials thermal expansion, the wire length *l* with a partial stretch and wire section variation. Thus *wTemp* has an effect on M_{ms} and both Bl and R_e, involving the *motor efficiency factor* term in the efficiency formula:

$$\eta_0 M = \frac{Bl^2}{R_e}$$

The 2nd temperature is linked to the environment working temperature at which the transducer is measured, it is called *air temperature* (*Temp*). It is important if we are measuring DUT at a different temperature, or for example we are going to install the loudspeaker in a different temperature due to environment conditions and we want to know the final sound pressure level or parameters variation. *Temp* involves the first term of the efficiency formula (because of the air density ρ_0 and the speed of sound c) and also the third term of the efficiency formula, because M_{ms} includes the mechanical mass M_{md} and air load mass (which varies with air density ρ_0 and consequently with the temperature *Temp*).

The 3rd temperature, available only in VVC 2.1, is ΔT (expressed in *Kelvin*) and it is related to voice coil temperature increase, due to *Joule heating*. Moving ΔT slider, *VVC* recalculates in real time all involved electrical parameters, as the DC resistance and related electric power and current variations, or some acoustical parameters, as the transducer sensitivity *dBSPL* reduction (due to power compression) or *Loss Factors* variation.

Moreover, *VVC* calculates also mechanical parameters variations due to *Joule heating*, as the voice coil winding height (*H*), the minimum inner diameter or maximum outer diameter, due to materials thermal expansion. This tool is very helpful for evaluating and optimize clearances inside the magnetic air gap. *VVC* computes parameters estimation assessing these 3 kind of temperatures, obtaining very accurate results.

To develop expressions for all temperature dependent parameters, the following assumptions are made: resistivity and dimensions vary as a function of temperature, depending on geometry, material thermal expansion, coefficient of thermal expansion, material temperature coefficient of resistance, material thermal conductivity, material electrical resistivity. Particularly resistivity and thermal expansion are linear functions of materials, respectively:

$$\delta_R = R_0(1 + \xi\ \Delta\theta)$$
$$\delta_L = \alpha\ L_0\ \Delta\theta$$

Where: ξ is the temperature coefficient of resistance, R_0 is the original resistivity, α is the coeffcient of thermal linear expansion, L_0 is the original length.

For both expressions $\Delta\theta$ is the temperature variation, including the 3 temperatures ($wTemp,\ Temp,\ \Delta T$), restricted in a range such that ensuring linear functions for $wTemp$ and $Temp$ and using a non-linear second order function for ΔT. In Joule heating of voice coil wire, using for example multi-layers voice coils, the external layers lose heat to ambient air and subsequently result in a lower temperature if compared to wire wound in an internal layer. This is not achievable with the available *VVC* input data and for convenience the software doesn't comprise free or forced convection in air, but heat dissipation by internal conduction only.

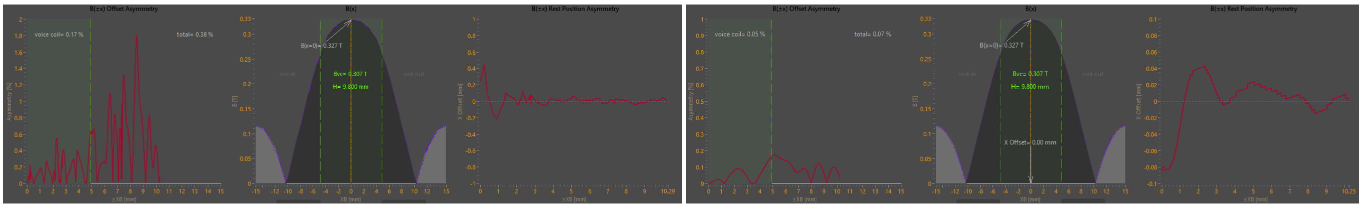
So B and S_d are the unique terms in efficiecy formula *VVC* doesn't consider as temperature dependent variables. Because S_d is considered as a pure dimensional input. On the contrary, the magnetic flux density B is affected by temperature in reality (with reversible temperatures coefficients and irreversible loss of magnetic assembly), but B variation depends on used magnetic materials and geometry topology information, which are external to *VVC* data, hence $B(x)$ values are assumed as temperature invariant.

Environment Humidity variable (*Hum*) is present among *VVC* inputs, it has less influence in the efficiency formula, thus we can rewrite the temperature dependent η_0 as it is treated by *VVC*:

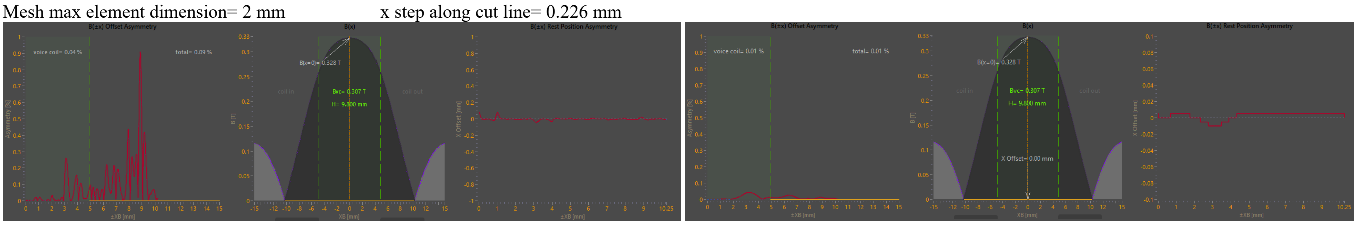
$$\eta_0 = \frac{\rho_{0(Temp)}}{2\pi\ c_{(Temp)}} + \frac{Bl^2{}_{(wTemp)}}{R_{e(wTemp,\ Temp,\ \Delta T)}} + \frac{{S_d}^2}{{M_{ms}}^2{}_{(wTemp,\ Temp)}}$$

The second term is the *motor efficiency factor* $\eta_0 M$, it represents also the *electrical damping* of the system and it is available in *VVC Transducer Motor* table.

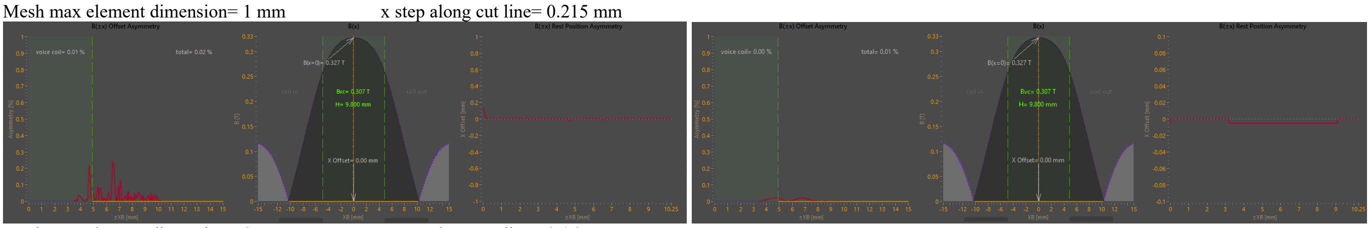
Now we can see how *VVC* processes elements simulated and imported from an external FEA software. This method is very important for processing data in a reliable way. For motor designs with an axis of symmetry it is always a good practice to operate with partial models, dividing them along the symmetry axis and using only a section of the entire model; but for the evaluation of an algorithm behavior related to symmetries a FEA of the whole symmetrical model is necessarily done and imported in *VVC*, the flux density *B(x)* is visible in **Figure 1**. In symmetrical designs small differences between the two opposite mirror sides of the *B(x)* and *Bl(x)* profiles could yield to plots values of asymmetries >0 %. These differences are due to finite element mesh, particularly FEA mesh nodes and their positions in space, then also to the geometry of the mesh elements, their dimension and distribution. In the left side of **Figure 1** are showed 4 different mesh elements dimensions (with max and mean values along the *B* cut line).



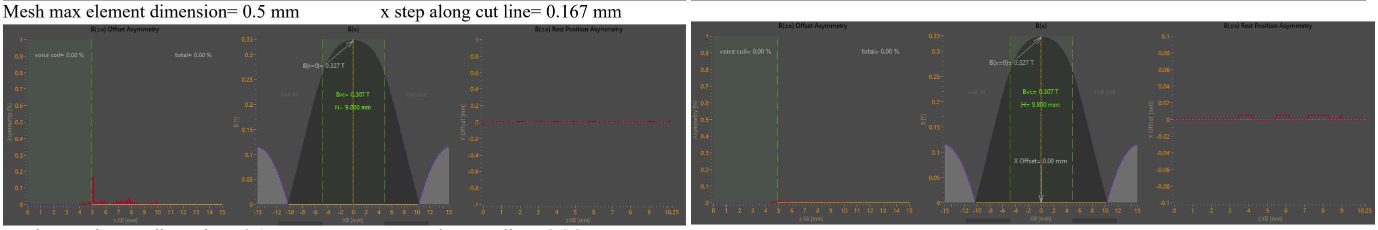
Mesh max element dimension= 2 mm x step along cut line= 0.226 mm



Mesh max element dimension= 1 mm x step along cut line= 0.215 mm



Mesh max element dimension= 0.5 mm x step along cut line= 0.167 mm



Mesh max element dimension= 0.1 mm x step along cut line= 0.065 mm

Figure 1: Asymmetry graphs, before (left side images) and after (right side images) the *ATF* filter is applied.

When a flux density is imported, *VVC* operates a resample of *B(x)* for setting cursor in an independent mode compared to imported *x* points step, then an automatic weighting filter is applied. Smoothing a curve could be dangerous, sometimes a great deformation of the curve occurs when a smoothing filter is used. The applied **Auto Tune Filter** (*ATF*) depends on inflection points biased to the curve gradient of the FEA imported data. This filter is suitable for reducing errors due to different FEA mesh methods. A first stage of the filter computes the absolute value of the arctangent of y/x, for angles in any of the four quadrants of the x-y plane, to obtain the curve gradient |m|, measuring the steepness of the curve and inflection points positioned along the curve steepness.

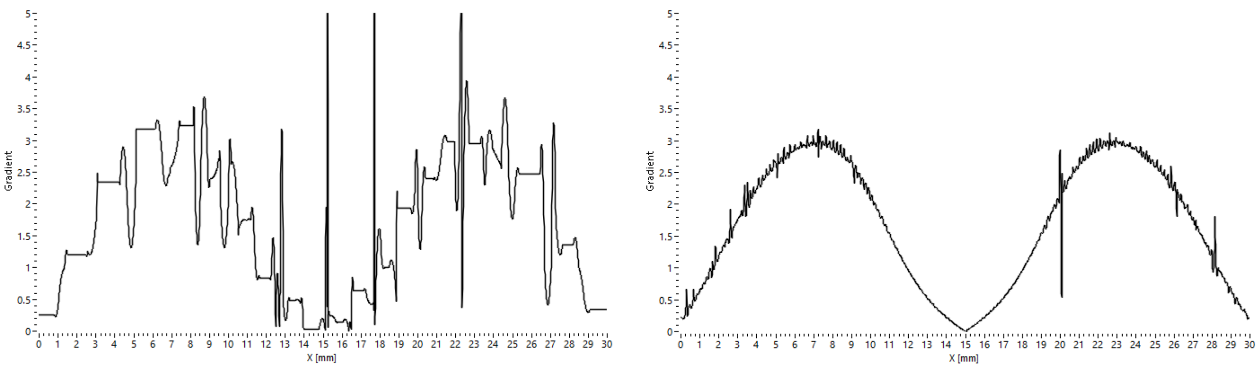


Figure 2: Gradient of the original coarse data without (a) and with the ATF filter (b).

The *ATF* of the imported magnetic flux density *B(x)*, simulated with external FEA software, is set according to a fitting model which works as a smooth of the data set (**X [mm]**, **Y [T]**) according to a minimization of the following function:

Auto Tune Filter (*ATF*)

$$ATF = \gamma \sum_{i=0}^{n-1} w_i \left(y_i - f(x_i)\right)^2 + (1-\gamma) \int_{x_0}^{x_{n-1}} \left(f''(x)\right)^2 dx$$

Gamma is the **balance parameter**, it depends on the evaluation of imported step, outliers number and inflection points amplitude

w_i is the i^{th} element of **Weight**. Weight depends on gradient amplitude
y_i is the i^{th} element of **Y**
x_i is the i^{th} element of **X**
$f''(x)$ is the second-order derivative of the cubic spline function, $f(x)$.

The gradient of the *ATF* filter is showed in **Figure 2** and the results of its application is visible on the right-side images of **Figure 1**. Using the coarse mesh (2mm max element), applying the *ATF* filter and moving the voice coil offset= 0.01mm coil-in, the current (red line) symmetry compared to offset= 0 (dashed blue line) is visible in **Figure 3**.

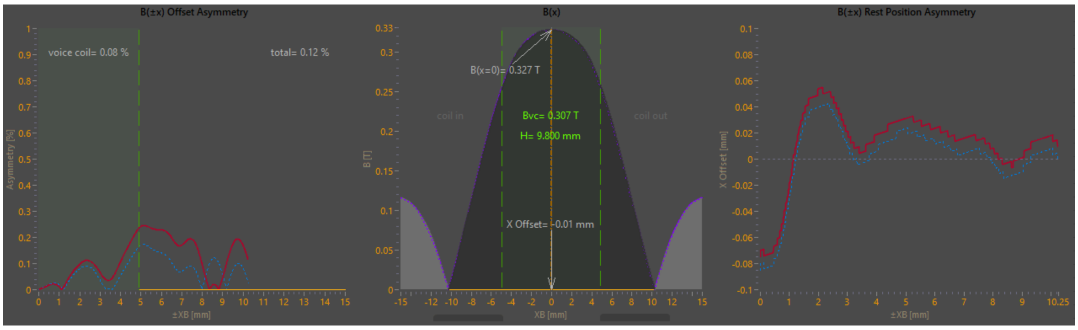


Figure 3: Asymmetry graphs (sides) of the imported magnetic flux *B(x)* (center), shifting voice coil offset= -0.01 mm and using a coarse mesh.

In the worst case, using a very coarse mesh, values of asymmetry peaks <0.2% could represent symmetrical $\pm x$ points. While using the finest mesh (0.1mm max element) and moving offset= 0.01mm coil-in, its symmetry is now showed in **Figure 4** in which is possible to appreciate very small differences.

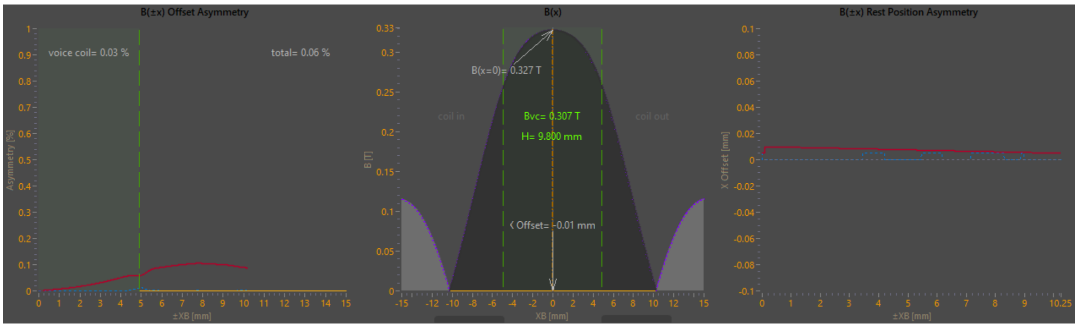


Figure 4: Same of figure 3, but with a fine FEA mesh.

Anyway, you can test your own CAD-FEA-*VVC* chain, designing, simulating and importing a symmetric motor flux density, for examining the symmetry goodness.

After the introduction of some of the key features about *VVC* data processing, now, we are going to see a novel technique for maximizing efficiency of a loudspeaker, using *VVC Wire Loss* and the *SPL* charts. *Wire Loss* chart was presented in 2014 in the *VVC* first version, then all bugs of the old version have been solved in *VVC* 2. For instance, a simple symmetrical magnetic circuit, with a 50 mm inner diameter voice coil is considered.

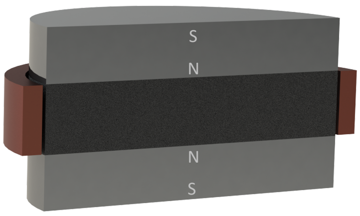


Figure 5: Symmetrical open-gap magnetic circuit.

As visible in **Figure 5**, it is an open-gap magnetic system, with two magnets in mirror arrangement having negative fluxes along the *B(x)* bounds. The negative values are sampled in absolute value and showed in light grey color in the positive *Y*. This is convenient for permitting evaluations of applied negative forces (it can be used for electromagnetic breaks) compared to the positive force, along the same voice coil displacement. Voice coil is without a former, only winding, and for the simulation the *B(x)* flux density cut line is selected in order to accept voice coils with different diameters. The design can accept 46.5 mm as the minimum voice coil ID. In *VVC*, after importing a *B(x)* for an air gap length of ±15 mm and arranging voice coil data, disabling the former, we can move the wire size cursor over the darkest bar in *SPL* chart, obtaining the highest SPL of 73.52 dB using a Ø 0.33 mm wire.

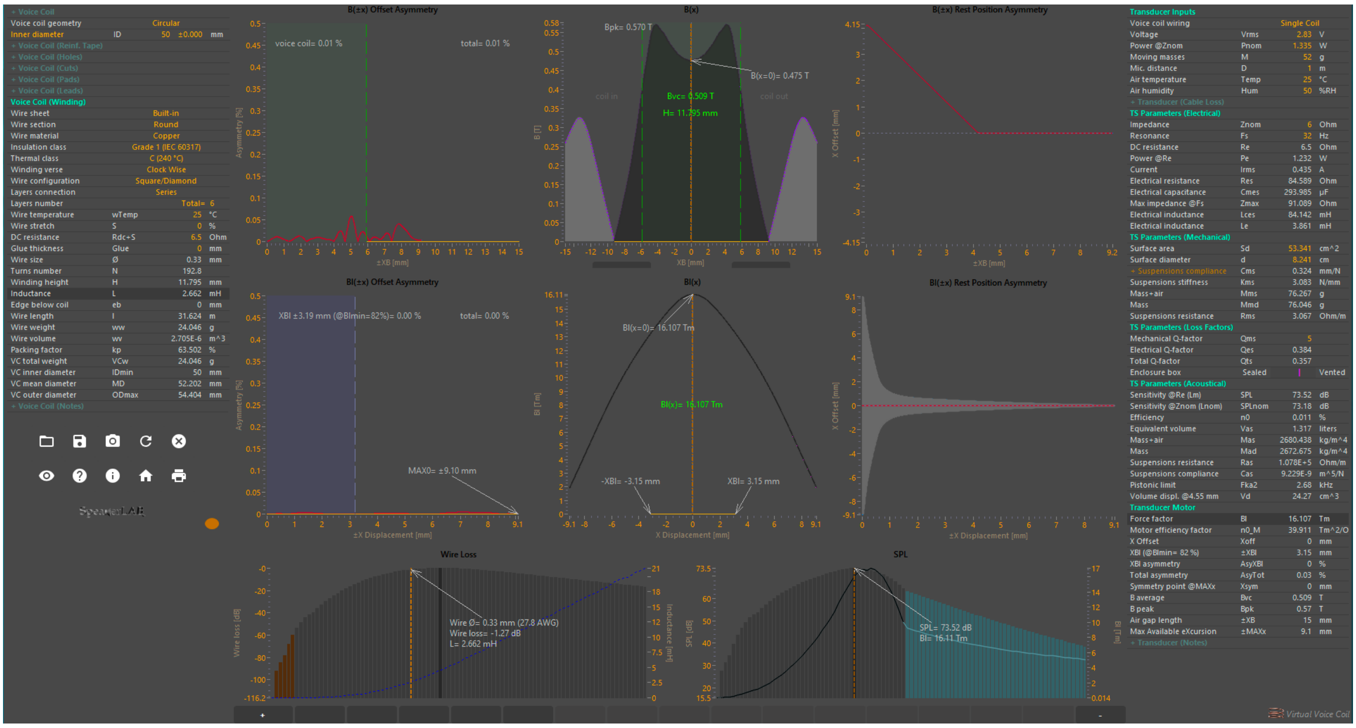


Figure 6: Cursor aligned with the darkest bar in *SPL* chart (bottom right chart).

As we can see from the *SPL* chart, bottom right of **Figure 6**, the cursor is aligned with the darkest bar. The darkest bar represents the maximum value among all wires. So, this is the maximum SPL, but is this also the maximum efficiency of the system? As we can see from the bottom left graph of **Figure 6**, the cursor in the *Wire Loss* chart is not aligned with the darkest bar. The dark bar in *Wire Loss* chart indicates the highest efficiency among all wires, that is the golden ratio linked to the selected voice coil electrical and mechanical parameters and independent of the magnetic flux. When both the two cursors are not aligned with related dark bars it means the potential efficiency of the system could be improved. Operating with some minor adjustments and using the two cursors alignment as target, doubling the number of layers and selecting a Ø 0.4 mm wire, now the two cursors are both aligned over the dark bars: this is the maximum achievable system efficiency! As visible in **Figure 7**, *Bl* passes from 16 to 24 Tesla per meter, the SPL passes from 73.52 dB to 74.32 dB, so we have added +0.8 dB and the voice coil inner diameter is bigger than 46.5 mm, thus the voice coil is physically feasible. Gaining the maximum efficiency of the system.

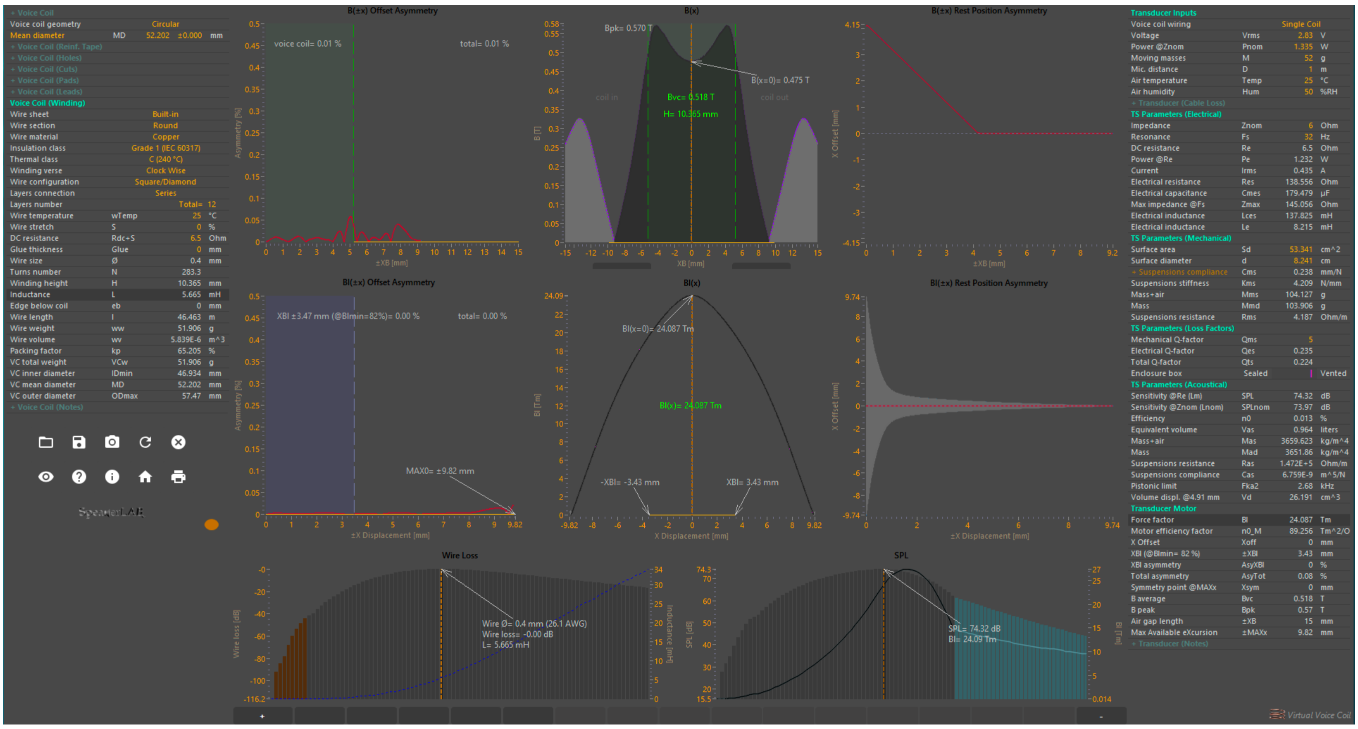


Figure 7: Cursors aligned with the darkest bars in both *Wire Loss* and *SPL* charts.

In the last example a magnetic circuit without a magnetic gap has been used in order to have the maximum degree of freedom for the voice coil OD. Anyway, using the presented method (both wire size cursors aligned over the darkest bars as target) it is possible to obtain the maximum efficiency for a loudspeaker with a magnetic gap, in this case, if practicable, it could be necessary to work also on motor design importing magnetic flux density variations due to OD restrictions. About this topic an important value to consider for the voice coil is the mean diameter, because if we set the mean diameter, it represents a fixed value for the FEA magnetic cut line. No matter if we change wire dimension or layers number. In the first loudspeaker simulation in **Figure 6**, the inner voice coil diameter is 50 mm. Keeping the inner diameter of **Figure 8**, if we change wire section to 0.4 mm and number of layers to 12, we obtain a new mean diameter= 55.268 mm of **Figure 9**.

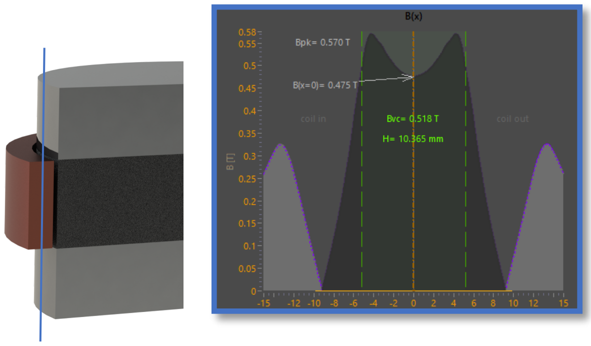


Figure 8: Cut line (blue) at mean diameter= 55.202 mm.

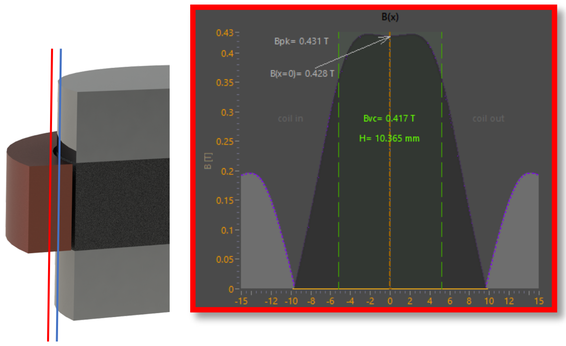


Figure 9: Cut line (red) at new mean diameter= 55.268 mm.

But 55.268 mm, is not the correct diameter of the imported FEA magnetic cut line of **Figure 6** and **Figure 8**, indeed, the density flux cut line at Ø55.268 mm is completely different, in **Figure 10** a *B(x)* comparison.

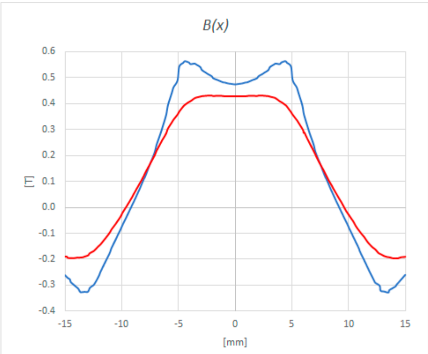


Figure 10: *B(x)* along the two different diameters cut lines.

The average flux, along a voice coil with 10.365 mm height, pass from 0.518 T to 0.417 T, giving a reduced *Bl(x)* and dB_{SPL} with different *TS* parameters. As a new feature, in *VVC 2.1*, it is possible to switch between inner and mean diameter. Indeed, in **Figure 7** is fixed the same mean diameter (55.202 mm) of **Figure 6**. Fixing the mean diameter ensure the voice coil position remains the same, regardless for example wire size or layers number change and it is possible to compare voice coils using the same magnetic flux density cut line.

Now we can see how to practically use *Bl(x)* asymmetry graphs, designing for example a typical loudspeaker motor in **Figure 11**, with a 25 mm voice coil diameter and Y-30 Ferrite 84x32.8x15 mm, a flat nucleus diameter of 24.4 mm and an upper plate diameter of 26.73 mm.

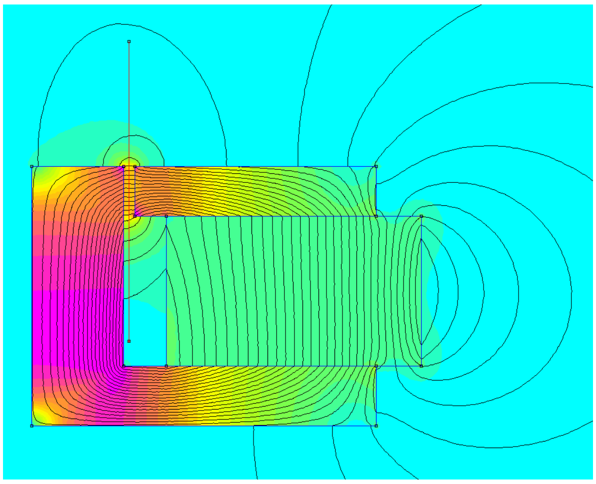


Figure 11: Typical 25 mm voice coil loudspeaker motor.

Using a FEA software we can plot the magnetic flux density along the line crossing magnetic gap and representing the available voice coil displacement. Then the same flux density profile is imported in *VVC* (considering that both period or comma decimal separators are accepted). At the moment, we can neglect loudspeaker parameters, they are not important for the symmetry analysis we are going to do. Adjusting the offset, it is possible to gain a better symmetry with a new rest position with offset= -0.50 mm, as showed in **Figure 12**.

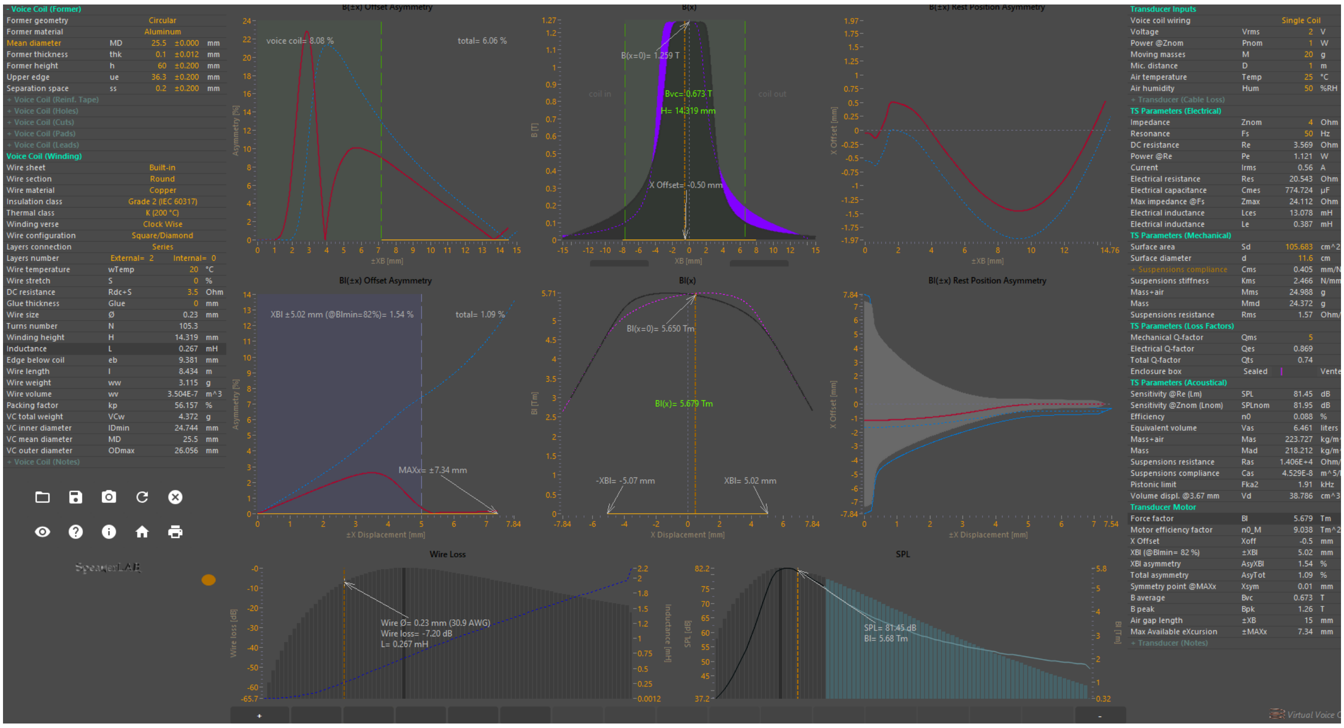


Figure 12: System arrangement using *B(x)* of Figure 11.

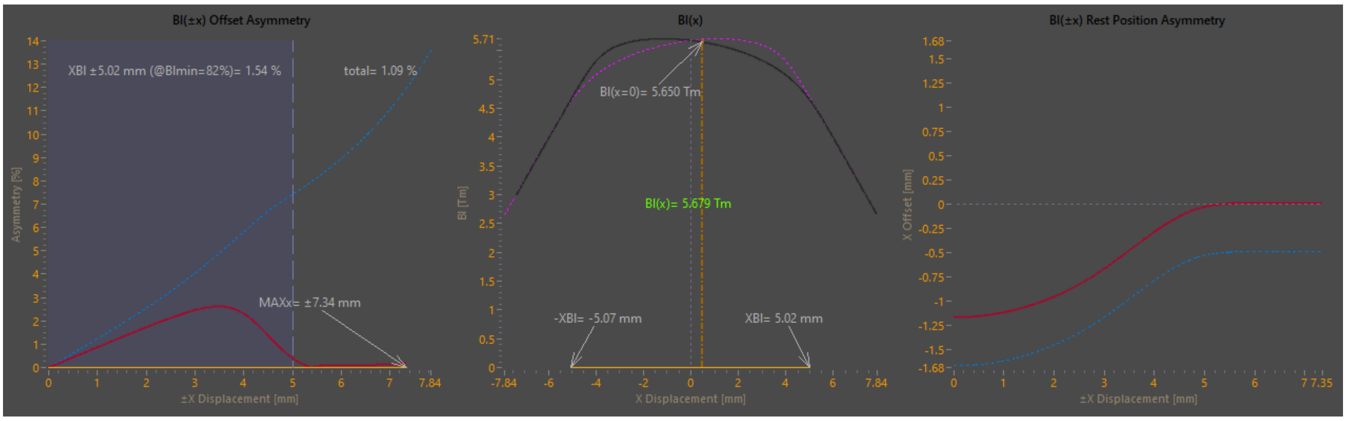


Figure 13: Detail of *Bl(x)* Asymmetry graphs in Figure 12.

In **Figure 13** we can observe a good symmetry for excursions >5 mm. But the symmetry is not good for displacements inside the Bl_{min}= 82% < 5 mm. As we already know, extending the nucleus as **Figure 14** it might help to symmetrize flux.

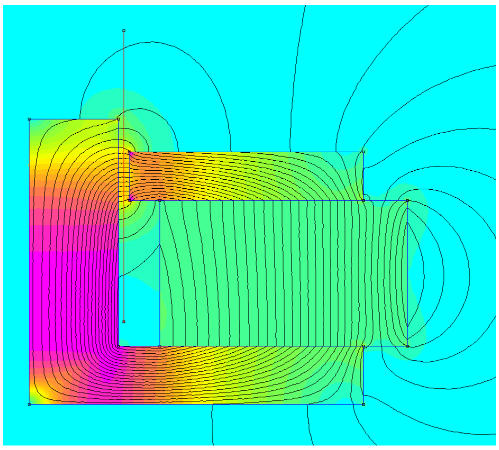


Figure 14: Same of Figure 11, but with a nucleus extension.

Importing flux and shifting offset= 0.03mm, total asymmetries= 0.11% are now in **Figure 15** about one order of magnitude lower than the flat nucleus.

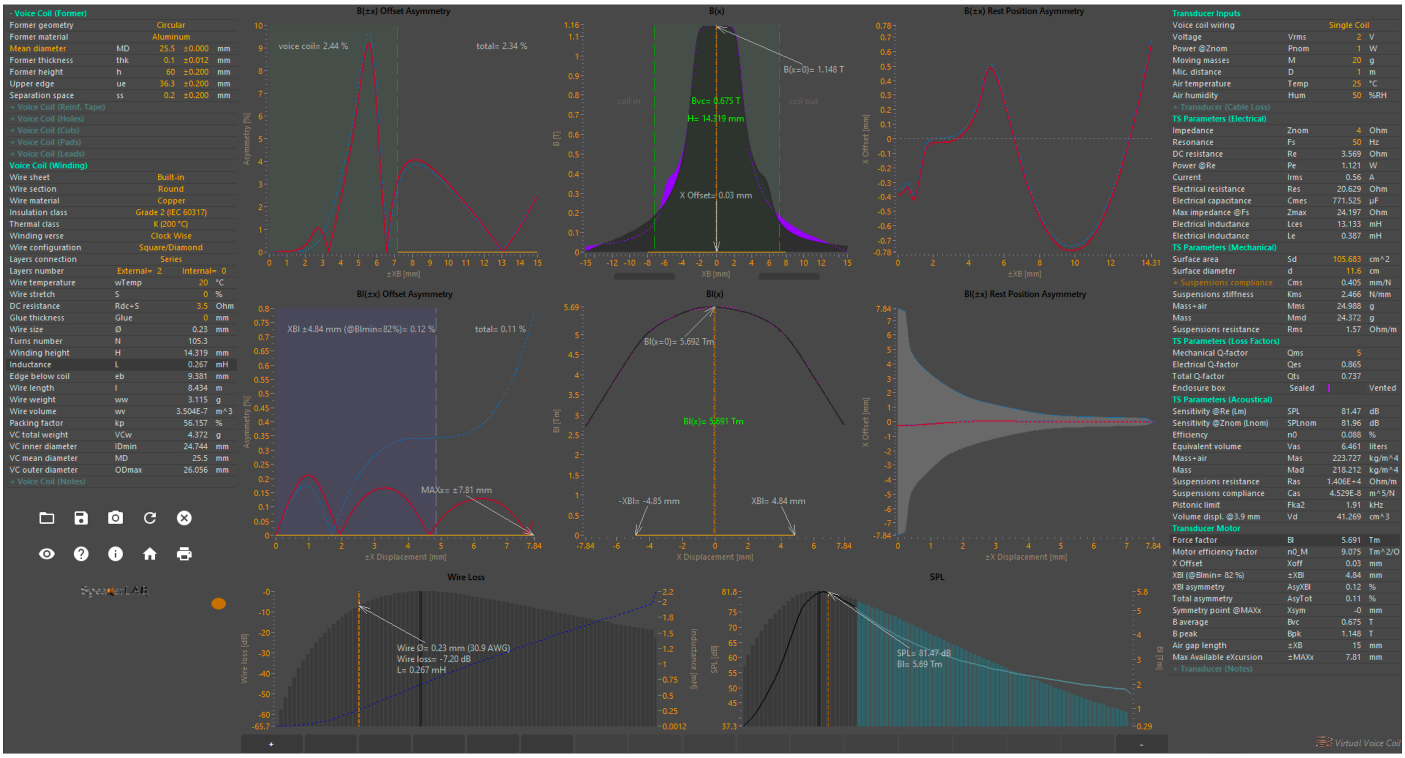


Figure 15: Setup using *B(x)* of Figure 14.

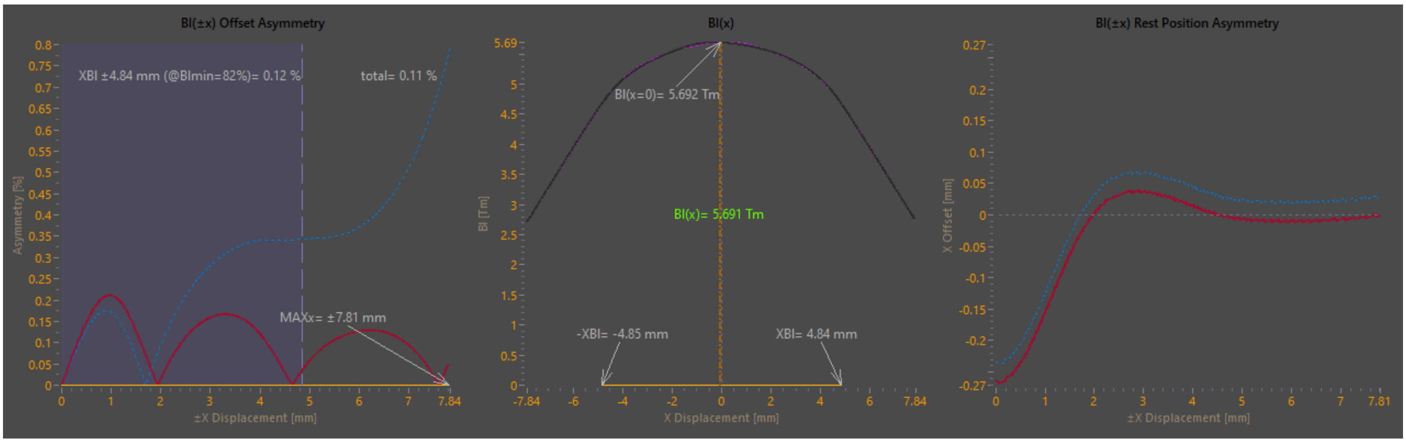


Figure 16: Detail of *Bl(x)* Asymmetry graphs in Figure 15.

Observing **Figure 16**: the two curves in *Bl(x)* graph seems overlapped, but as we can see from *Bl(±x) Offset Asymmetry* graph, we still have some peaks of about 0.2% and total asymmetries= 0.11 %. Moreover, the *Bl(±x) Rest Position Asymmetry* graph shows some oscillations with a rest peak of -0.27 mm.

Now if we modify the nucleus extension with a sloped uppercut like in **Figure 17**, importing flux and shifting offset= -0.13 mm

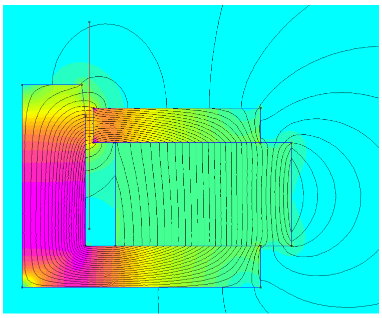


Figure 17: Same of Figure 14, but with a sloped uppercut nucleus extension.

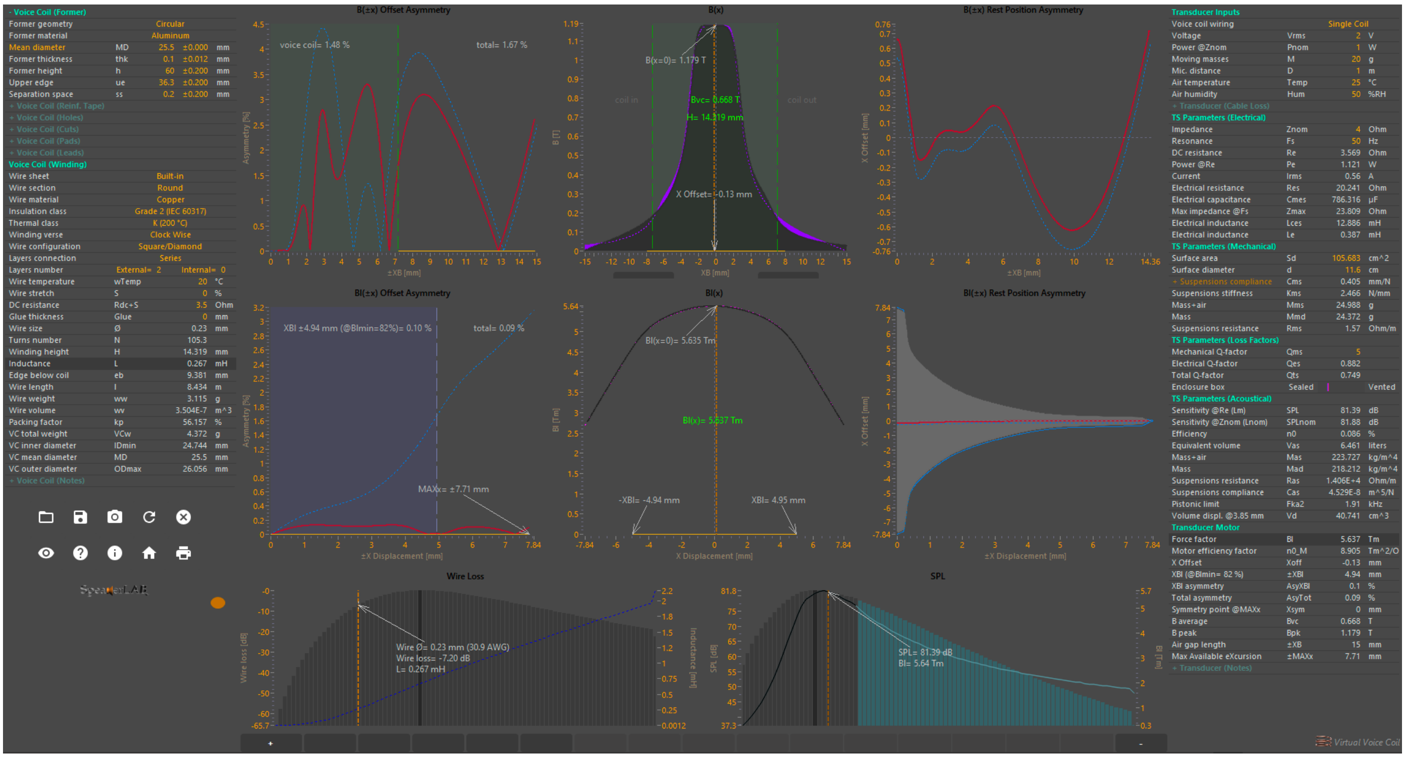


Figure 18: Setup using *B(x)* of Figure 17.

We obtain the best symmetry for this motor design, as visible in **Figure 18**. Reducing *Bl(x)* asymmetries for the full displacement of the voice coil with a flat *Bl(±x) Offset Asymmetry* curve, see **Figure 19**, and the minimum total asymmetry recorded 0.09 % among the various designs. The *Bl(±x) Rest Position Asymmetry* is also improved using the sloped uppercut, less oscillations and a reduced amplitude, it is now -0.15 mm.

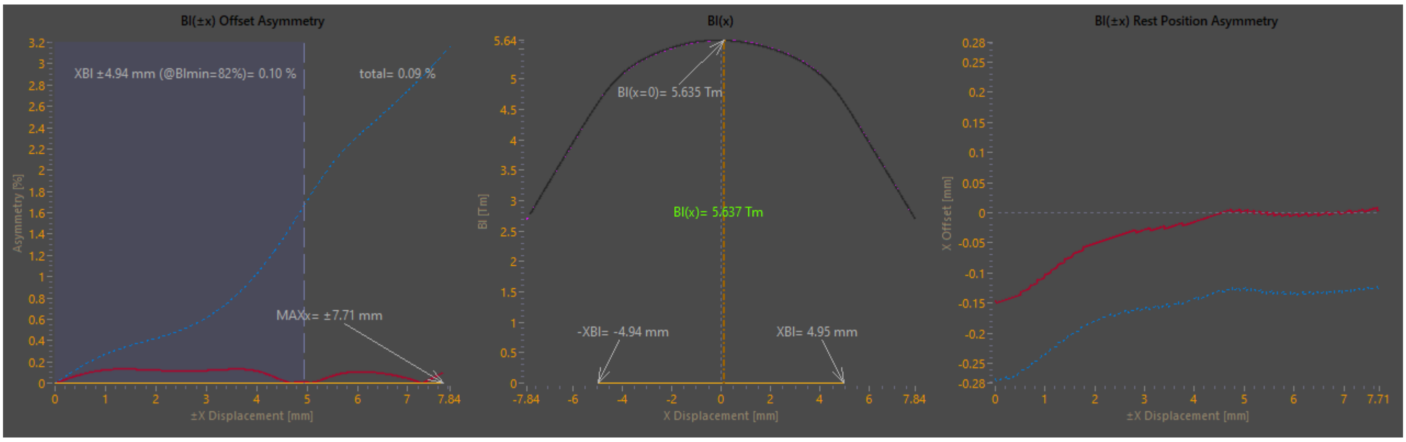


Figure 19: Detail of *Bl(x)* Asymmetry graphs in Figure 18.

These are some simple examples just show how to use *VVC* asymmetry graphs for optimizing a loudspeaker motor design.

In new *VVC* version 2.1, it is possible to add more than one spider (max 3 spiders), then surround and spider *rates* measure their contribution on total system. When *Cms* window is expanded for the first time in *VVC*, the default value of the surround rate is 20% of the total *Cms* or *Kms* and the spider rate is 80%. It is a suggested starting point, also suggested by Vance Dickason in "Loudspeaker Design Cookbook".

Another feature of *VVC* 2.1 is the *Transducer Cable Loss*, it is referred to the cable from amplifier to loudspeaker terminals. Cable loss is suitable for dimensioning cables in a project, controlling for example SPL reduction or how the *Loss Factors* will change. *VVC* automatically recalculates related loudspeaker parameters. For the cable core material 4 options are available and its electrical conductivity is referred to air temperature (*Temp*) at which the transducer is measured. We can set the cable *diameter*, alternatively we can set the *American Wire Gauge*, or the core *section*. Paying attention, to preserve the right quantity of total damping, it is an important value to consider, in order to control back *Electro Motive Force* of transducer moving masses, especially in sub-woofer applications.

Finally, *VVC* 2.1 offers 3 options for *Voice Coil Wiring*, selecting a *single* voice coil as standard configuration, otherwise it is possible to combine two voice coils in *parallel* or in *series*. A new video tutorial about *VVC* is now available on www.spekerlab.it website, which integrates with more examples the material presented in this article.