AN-030

Balanced Armature Tweeters in TWS Earphones – Application Note

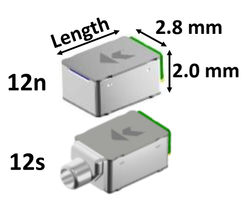
This application note describes best practices for the implementation of Balanced Armature (BA) tweeters into True Wireless Stereo (TWS) earphones. It briefly introduces the most common specifications to consider when choosing a BA tweeter and presents design cases on placement, crossover design, and channel acoustics to help optimize the TWS treble performance.

Introducing a BA Tweeter in TWS

This guide assumes the reader has a general understanding of BA tweeter construction and electroacoustic performance and are considering their implementation into a TWS earphone design.

Choosing a BA tweeter is typically straightforward when compared to the various design parameters to consider when choosing a woofer or a full-range driver for an earphone.

Knowles provides three BA tweeter options for TWS implementations which are primarily differentiated by their first peak resonance, with expected crossover frequencies, part dimensions, and electrical resistance shown in **Table** 1.



Model	X-over	Length	DCR
RAN	4.5 kHz	5.1 mm	12 Ω
RAU	6.5 kHz	5.1 mm	12 Ω
RAX	5.5 kHz*	4.0 mm	12 Ω

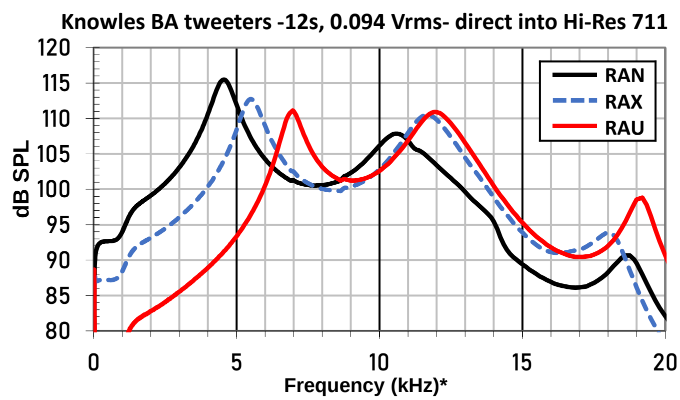
Table 1: Knowles BA tweeter options

The RAN is a wide-band tweeter with a 4.5 kHz crossover and 28.6 mm^3 in volume, this tweeter motor design has a nice balance between high vocals and upper treble and has been successfully implemented by top tier earphone manufacturers.

The RAU is a high-frequency tweeter designed with a 6.5 kHz crossover and same size as the RAN. It has been optimized with more upper treble output, as seen in **Graph** 1.

The RAX is balanced between a RAN and RAU tweeter performance with a 5.5 kHz crossover and 1.1 mm shorter in length, which leaves more room for packaging adjacent components.

*Note: The RAX also comes with higher resonance motor construction options for 8.5 kHz up to 12 kHz crossovers.



Graph 1: BA Tweeters direct into Hi-Res 711 response. *Shown with a linear frequency distribution to ease distinction between results at high-frequencies.

When selecting one of the BA tweeters there are three important design choices to consider:

1. Port location and packaging
2. Crossover design
3. Nozzle and eartip acoustics

1) Port location and packaging - A BA tweeter does not need back-venting and has a self-enclosed back volume. This allows the BA tweeter to be packaged inside the woofer's front volume cavity without the need to create special back-venting channels. The treble performance can be maximized by placing the BA sound port closer to the ear tip opening than to the woofer. Avoid having a large air cavity (i.e. 100 mm^3) between the tweeter port and the ear tip opening.

It is often desirable to place a microphone near the ear tip opening to improve the cancelling performance of ANC systems. It is advantageous to coordinate the packaging of the BA and the microphone to minimize space requirements yet preserve open air flow to the ports of both devices.

The design of the earphone nozzle, or acoustic port outlet, will typically determine the preferred BA orientation and port location. The standard BA tweeter port location is at the 12 o'clock facing surface (12n), depicted by the left image in Figure 1, and it comes with a choice of metal tubing attachments (12S). The left image of **Figure** 1 shows the BA packaged "in-line" with the earphone's nozzle, which allows for smaller diameter nozzle and narrower opening eartip designs.

Knowles provides the option to change the output port location to the top cover (0J) instead of the front side of the BA tweeter. This gives the TWS designer the option to orient the BA's diaphragm parallel to the woofer's diaphragm, as shown in the right image of **Figure** 1 below, which is better suited for shorter nozzle and larger opening eartip designs.

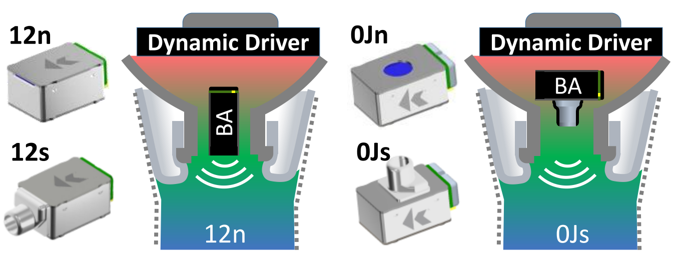
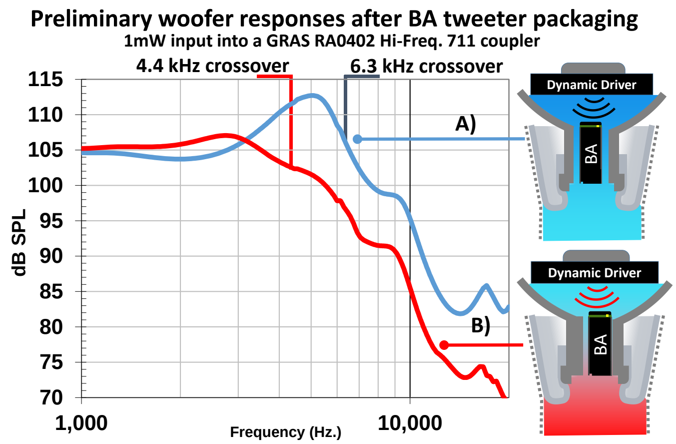


Figure 1: Front port 12 vs top port 0J option and example of woofer and tweeter earphone packaging.

It is important to avoid close proximity between a BA tweeter and non-shielded magnets, as close proximity can increase THD or degrade performance until moved away. Leaving a 0.5 mm gap between the BA and surrounding non-shielded magnets is usually sufficient. Closer placement may require additional experimentation or modeling to minimize magnetic interaction. Contact a Knowles team representative for additional BA tweeters options and mu-metal shielding designs if a strong magnetic field (i.e. >1,000 gauss) exposure is inevitable for an earphone design.

After the location, port orientation, and magnetic field exposure are defined, it is best to measure a preliminary woofer TWS earphone response. This should be done with all components packaged within the acoustic passage between the woofer and ear canal, to be near their final shape and desired location. The woofer's response can change as components, including the BA Tweeter, are packaged within the woofer's front volume acoustic channel. As demonstrated by Graph 2, a constricted passage B) in red, equivalent to a 1 mm diameter by 5 mm length channel, created when a non-powered 12n port BA tweeter is packaged inside the earphone's nozzle can act as a low-pass filter to the woofer response when compared to a non-constricted passage A) in blue.



Graph 2: Preliminary earphone woofer response with a non-powered BA Tweeter packaged inline with the nozzle with A) non-constricted acoustic channel and B) constricted acoustic channel creating a low-pass filtering effect.

This preliminary woofer measurement can be used as a guide for BA tweeter selection. The frequency where the woofer response falls should be used to select the tweeter with the best corresponding response. A tweeter with a lower resonant frequency should be selected for a woofer with a lower cutoff frequency. For example, the RAN, with a 4.5 kHz crossover motor design, is the best choice for the constricted B) woofer design from **Graph** 2, as shown in Figure 2, while the RAU, with a 6.5 kHz crossover motor design, is a better match to the non-constricted A) woofer response.

2) Crossover design

One of the first steps to design a successful woofer and BA tweeter crossover is to make sure the woofer and tweeter voltage sensitivities are balanced before designing the electrical crossover filters.

Voltage sensitivity - The voltage sensitivities of the woofer or tweeter are defined by their input impedance. The input impedance for a BA tweeter or dynamic driver (DD) woofer changes depending on the transducer's coil design.
The BA motor input impedance rises with frequency due to its high inductance. The high inductance is evidence of the efficient electromagnetic conversion (electricity to force) of BA devices.

By selecting the right impedance one can find the right balance between the woofer and tweeter while maximizing the electrical efficiency of the TWS design. A good starting value for the DC resistance of the DD woofer that balances well with the 12 Ω BA tweeters is 25 Ω, with a range from 16 Ω to 50 Ω.

The BA tweeter has a wide range of impedance options. A common value is 12 Ohms DC resistance, but that can be modified to any desired sensitivity within the 3 – 200 Ohms range.

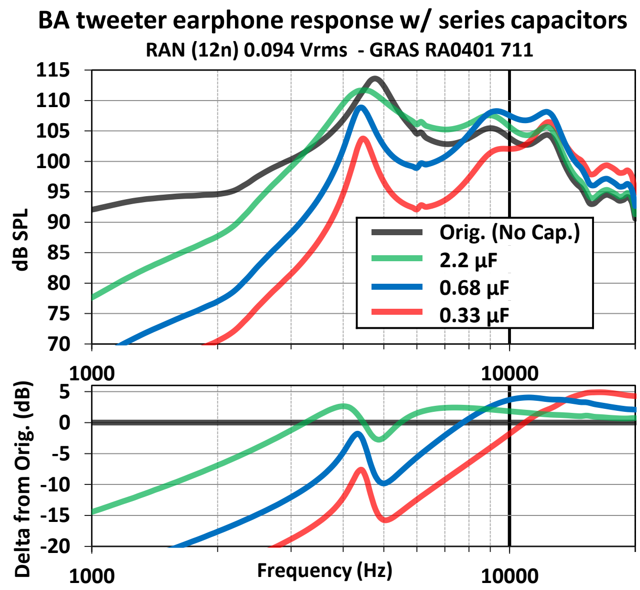
Note: Unlike small and light moving coil designs, BA devices will not be damaged by a large voltage input signal (i.e. 1-5 Volts) and do not need over-voltage protection limits.

Electrical Filters - In TWS earphones both woofer and BA tweeter are often connected to a single amplifier instead of wired to two DSP filters. A simple crossover network is used to send only high frequency energy to the tweeter.
It is common in 2-way loudspeakers to design electrical crossovers with a low-pass filter to the woofer and high-pass filter to the tweeter. The low-pass filter requires large inductors that are impractical for a TWS implementation. Acoustic dampening screens or constricted channels have been used as a low-pass filter alternative for wired multi-driver earphones. Acoustic low-pass filters have not been widely implemented in TWS earphones. One reason is the phase shift caused by constrictions or acoustic filters to the woofer's response at the frequency range of suppression that may reduce ANC stability.

In contrast, high-pass electrical filters in loudspeakers can easily be scaled down to multi-layer ceramic capacitors sizes that are compatible with TWS circuit designs. As shown in **Graph** 3, three different capacitor values 0.33 µF in red, 0.68 µF in blue, and 2.2 µF in green are placed in series with a front port 12 Ohms DCR BA tweeter (RAN) packaged inside an earphone and compared to a non-filtered response, in black.

The difference between the filtered and non-filtered response is shown in the bottom respective curves of **Graph** 3. The capacitor provides a first order high pass filter, reducing the low frequency response of the tweeter at a slope of 6 dB/octave below the cutoff frequency.

The impedance of BA Tweeters provides an useful resonance when combined with the series crossover capacitor. The inductance of the BA tweeter, with a 12 Ohms DCR or higher, forms a damped resonator with a broad boost to the BA tweeter response. This boost is effective in the octave centered at 2 times the filter's cutoff frequency. This provides a 5dB increase in the treble output for the RAN example in **Graph** 3.



Graph 3: Series capacitor high-pass filter effect on BA tweeter

Knowles provides lumped parameter circuit equivalent models of BA tweeter and simple acoustic elements that can be used as supplemental guidance on what treble output to expect from different electrical filter designs, including the series capacitor high-pass filter covered in this application note.

Using the results from **Graph** 3 as a reference, the 2.2 µF capacitor is the best choice from the three series capacitor high-pass filters choices as it slightly flattens the first peak with minimal treble performance degradation.

A RAN with a 4.5 kHz crossover also appears to be a great candidate to pair with the constricted B) woofer response of **Graph** 2, with combined response, wiring schematic, and packaging illustration shown in Figure 2. Note: in this design the woofer's back-vent resistance was slightly increased to improve the woofer's 1-2 kHz output.

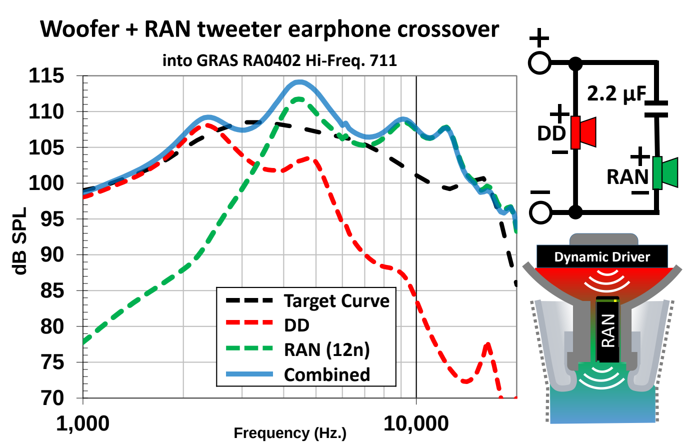


Figure 2: RAN and woofer crossover example

In contrast, when using the non-constricted A) woofer reference curve from **Graph** 2, we need a tweeter with a higher resonance.

The best BA tweeter candidate would be an RAU tweeter with a 6.5 kHz crossover. For this specific design, a similar electrical filter with a series 2.2 µF capacitor was also chosen as the best candidate, with combined response shown in Figure 2.

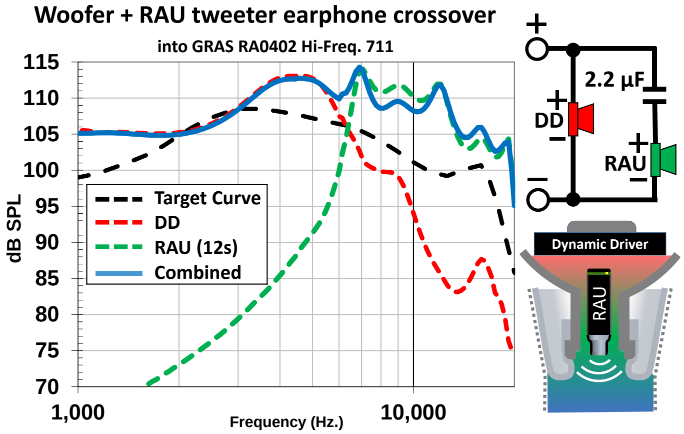
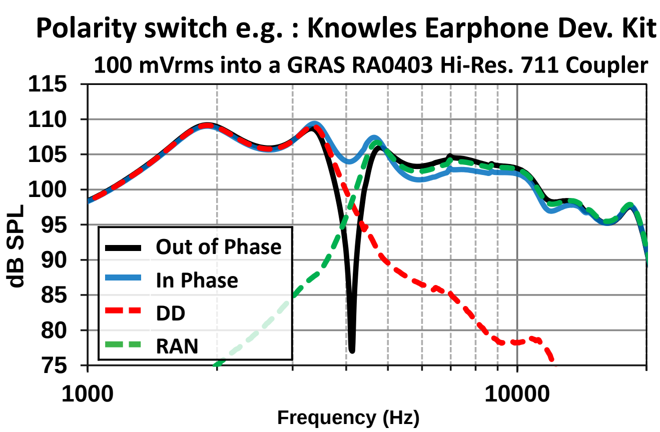


Figure 3: RAU with woofer crossover example

The ideal crossover design provides a smooth and flat transition from the woofer to tweeter response, with a perfect addition of their responses at the crossover frequency. This requires their response to be in phase and not out of phase from each other during the crossover bandwidth at which their responses are close in magnitude.

While both RAN and RAU crossover examples have been successful with the chosen wiring polarity to the input signal, the best wiring polarities can change depending on the woofer and series capacitor selection.

It is clear when the two drivers are out of phase from each other as their combined responses will create a notch, or valley, in the response, as shown by the "in phase" and "out of phase" example in Graph 4.

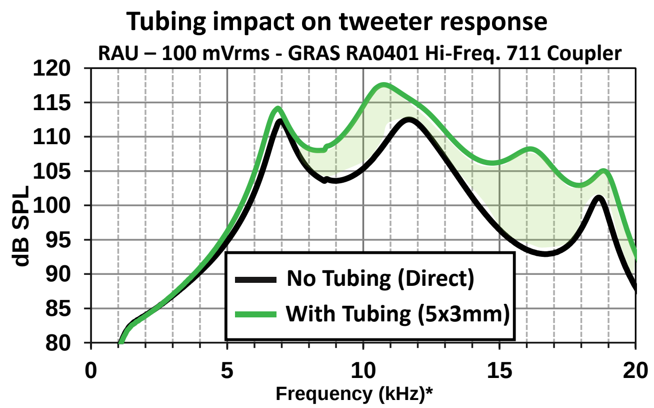


Graph 4: Importance of polarity wiring to avoid notches in the combined woofer and tweeter earphone response.

Once the crossover design has been completed, adjustments to the nozzle and eartip acoustics can be used to further refine the high frequency response.

3) Nozzle and Eartip Acoustics

Adjustments to the acoustic pathway between the BA port to the ear canal can be used to optimize the TWS earphone's treble response. As shown in **Graph** 5, a 5 mm length x 3 mm diameter path adds additional treble, highlighted in green, to the BA tweeter response not seen during a direct measurement to the ear simulator.



Graph 5: Nozzle and eartip tubing impact on tweeter response. *Shown with a linear frequency distribution to ease distinction between results at high-frequencies.

The earphone acoustic path can be divided into two sections: nozzle and eartip acoustics, as illustrated in Figure 4.

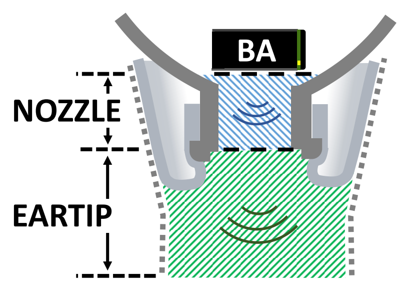


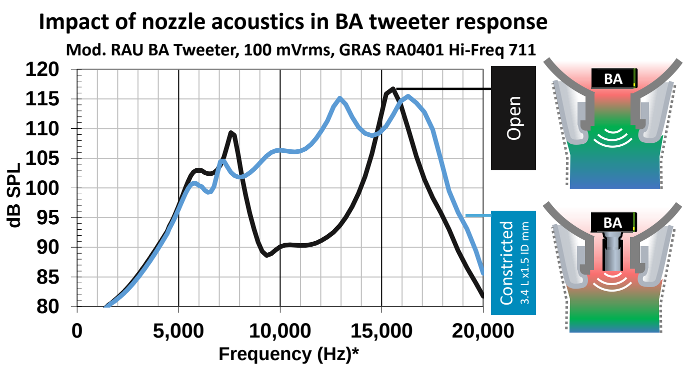
Figure 4: Acoustic channel segments likely to impact treble

Nozzle acoustics - The acoustic channel from the BA tweeter port up to the inlet port of the eartip cavity is an important factor to consider when optimizing the earphone's treble response.

The nozzle channel can introduce non-intuitive changes to the earphones treble performance, with tubing boosting the response and large openings introducing undesired valleys to the response. The choices for BA tweeter port location, and choice of BA tweeter will depend heavily on the size of eartip and nozzle connection interface design. An ideal nozzle for a BA Tweeter would be a separate channel from the BA tweeter port that gradually grows to the earphone's nozzle diameter.

Implementing such channel might be difficult, but adding tubing to the BA port can often help the treble response.

An example of using tubing is shown in Graph 6. A Knowles BA tweeter (RAU) modified with a top port (0J) is placed inside an open nozzle (black curve). The black curve shows the response if no tubing is added. The blue curve shows the improvement gained by introducing a 3.4 mm length and 1.5 mm in diameter acoustic tube (blue) to simulate a constricted nozzle design. For this specific eartip and BA Tweeter configuration the constricted channel makes a significant impact to the treble response with over 15 dB SPL boost to the 9-14 kHz bandwidth.



Graph 6: Impact of nozzle acoustics in BA tweeter response, with black curve measured without tubing and blue curve with a 3.4 mm length and 1.5 mm diameter tube extension.

Eartip acoustics – The acoustic path between the earphone's nozzle and ear canal after the eartip is compressed into the ear, or ear simulator, is one of the main contributors to the variability in the treble performance of earphones.

A 12n BA tweeter (RAN) was sealed to an earpohone nozzle, showed as green in Figure 5, then inserted into 5 different eartips of varying size and shape. The nozzle was customized with an end cap feature used to keep the insertion depth of the eartip into an external ear canal simulator (GRAS GR0408) consistent across measurements.

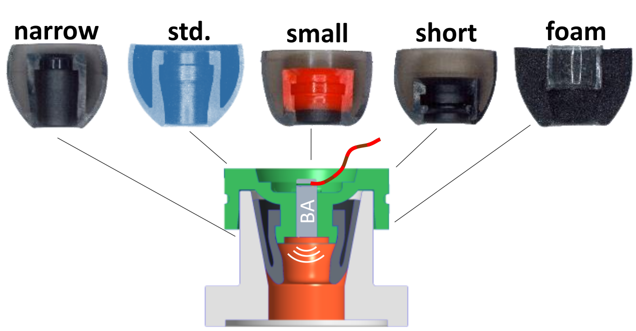
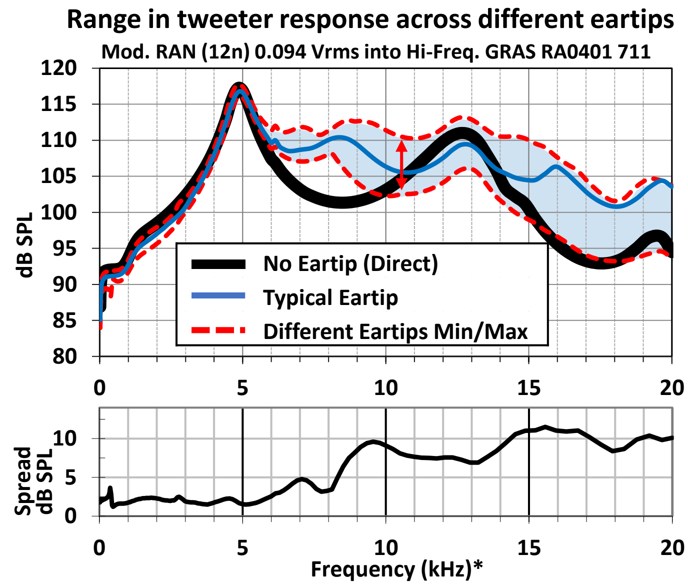


Figure 5: Shapes of eartips used in eartip acoustics study

The different ear tips caused the treble response to vary over the range shown in **Graph** 7. The range between the maximum and minimum (shown as red dashed curves) is shaded light blue on the top graph, and its magnitude is plotted below. The dark blue curve represents a typical response, and the black cruve reprents a direct response, without eartip or ear canal simulator. There is a ~10 dB spread in the treble performance from 9-20 kHz due to the differences in eartip designs.



Graph 7: Spread seen in the BA tweeter earphone response inserted into different shape and size eartips. With range between maximum and minimum shaded in blue and magnitude plotted at bottom. *Shown with a linear distribution to ease distinction.

With proper attention to BA tweeter selection, crossover design, tweeter positioning, and housing design, one can create an earphone with a smooth and extended high frequency reponse. Knowles representatives can help with further guidance, simulation models, earphone demos, and any additional information needed to help your team achieve a better earphone response.

Need additional information?

Please contact a Knowles representative if your team wishes to implement a BA Tweeter in your TWS design.

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