Using MEMS Microphones in Directional Applications

INTRODUCTION

A majority of MEMS microphones are inherently omnidirectional by virtue of having a single sound port (typically located on either the top or bottom of the package) which allows sound pressure to push and pull the diaphragm. This type of microphone is also known as a pressure microphone because its electrical output is proportional to the pressure present at the sound port.

The ICS-40800, on the other hand, is a dual port MEMS microphone offered by TDK which inherently has a bi-directional polar plot. This type of microphone is known as a pressure gradient microphone because its electrical output is proportional to the difference in pressure between the front and back of the diaphragm.

The following application note describes the general theory of operation as it relates to beamformers and an example of how to employ the ICS-40800 to achieve a cardioid-shaped polar plot for directional microphone applications.

PRINCIPLES OF DIRECTIONALITY AND BEAMFORMING

To fully appreciate and understand directional sound pickup, it is essential to first become familiar with the principle of an endfire beamforming array. Please refer to our Application Note AN-1140.

BASIC MEMS PICKUP ACOUSTICS

Within a MEMS microphone, tiny changes in air pressure that enter the sound port stimulate the diaphragm to move back and forth which then produces an electrical signal. Considering the scenario of a single-port MEMS microphone in Figure 1, it's no wonder why the polar pickup pattern is omnidirectional (Figure 2) – the microphone yields the same sensitivity or output level independent of the angle of incidence (for wavelengths significantly larger than the size of the package). Note: This omnidirectional response applies to both a single bottom or top port microphone, though a bottom port is used for the example below.

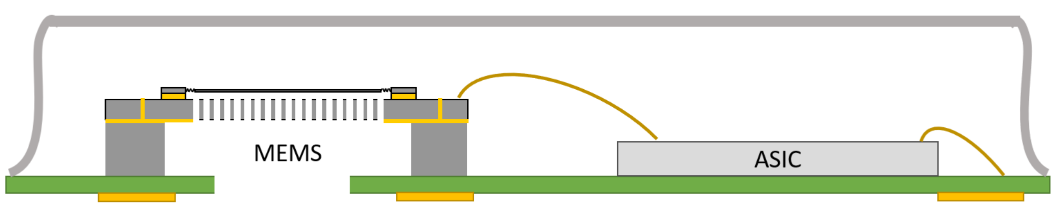

Figure 1: Model of a bottom-port MEMS microphone

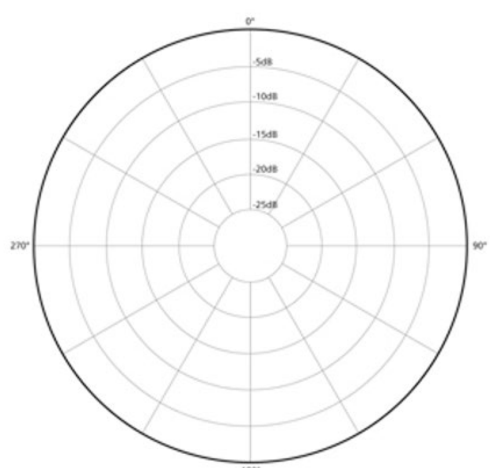

Figure 2: Omnidirectional polar plot of a single-port MEMS microphone at 1kHz

Now, let's consider the scenario of a dual-port MEMS microphone:

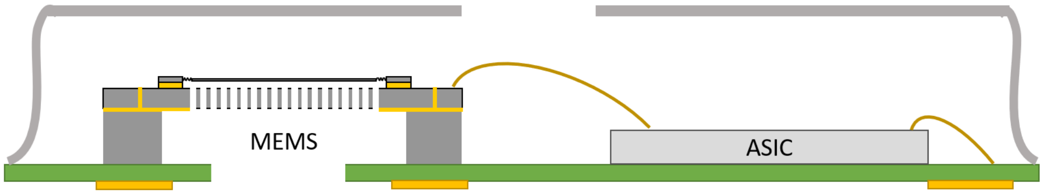

Figure 3: Model of a dual-port MEMS microphone

By introducing a second sound port to the top of the microphone package as shown in Figure 3, the diaphragm becomes subject to the difference in pressure on each side, otherwise known as the pressure gradient.

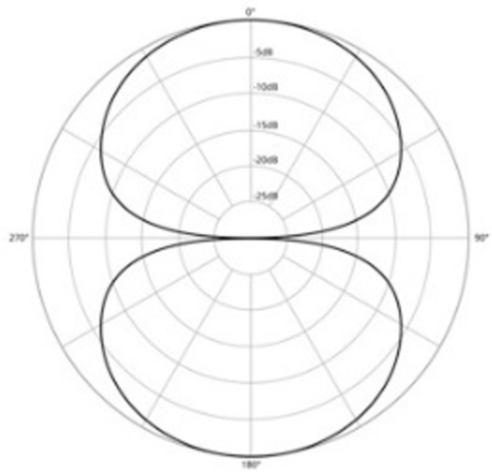

Figure 4: Bi-directional polar plot of a dual-port MEMS microphone at 1kHz

The microphone yields a different polar response, known as a bi-directional or "figure-8" response. The front and back sound ports are aligned with the 0° and 180° lobes in the response as shown in Figure 4. The 180° lobe has a negative polarity with respect to the 0° lobe, and the nulls at 90° and 270° occur because the instantaneous sound pressure is identical on each side of the diaphragm for waves arriving at these angles. So, at these nulls, there would be a zero pressure difference across the diaphragm and no resulting motion.

Unlike a single-port pressure response, the gradient response produced by the dual-port microphone falls off at 6dB/octave as frequency decreases. The response decreases proportionally with frequency due to lower frequencies having longer wavelengths. As the wavelengths get longer, the difference in pressure between the front and back becomes smaller.

DIRECTIONALITY SPECTRUM

By having the top port of the microphone completely sealed, there is no exposure of sound pressure to the back of the diaphragm, so an omnidirectional response is achieved. On the other side of the continuum, when the diaphragm is fully exposed on both bottom and top sides, a purely bi-directional pattern is formed.

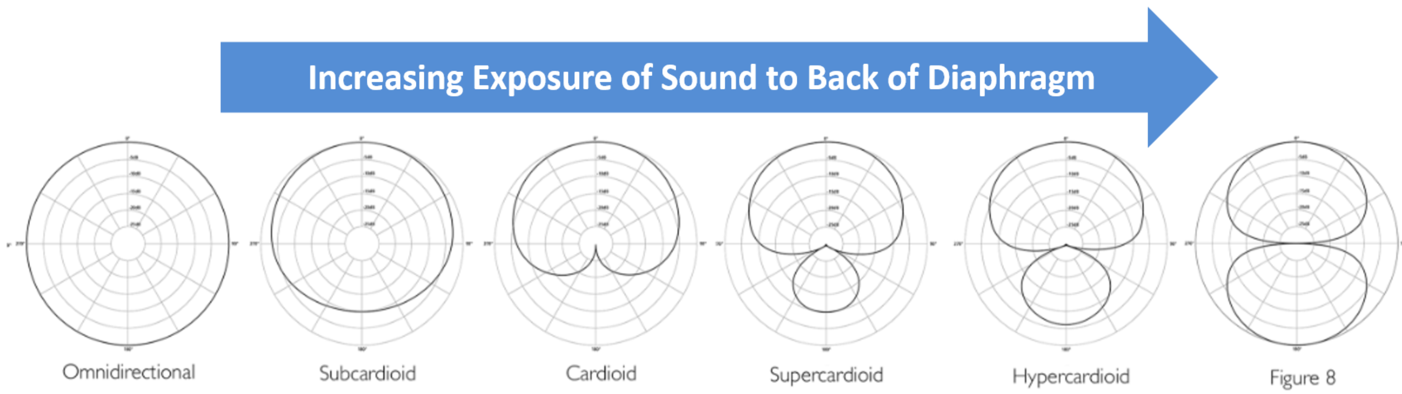

Figure 5: Various microphone polar responses

Within those two extremes, there lies a vast number of acoustic housing designs that can produce a directional characteristic suitable for any application. Our example application is detailed in the second half of this application note to demonstrate a simple example of achieving a cardioid-shaped directional pickup pattern with a 3D printed microphone capsule.

HOW BEAMFORMERS ARE RELATED

It's fairly common to find beamforming arrays in a variety of modern consumer electronics devices, but TDK has developed a novel method for achieving the same directional pickup capability with the ICS-40800. Instead of spacing multiple microphones in an endfire beamforming array by a fixed distance and incorporating n-sample delays (as mentioned in AN-1140) electrically to achieve directionality, the ICS-40800 integrates this capability into a single package. With the proper mechanical system design to fine tune the sound path length and exposure to the rear of the diaphragm, this mechanical “delay-and-sum” system achieves enhanced sensitivity versus angle of incidence without needing multiple microphones or a DSP.

As noted in AN-1140, the linear spacing between microphones plays a critical role in determining the initial null frequency. Comparing the ICS-40800 with the beamforming array, the distance which sound would have to travel between the front and back of the diaphragm (depicted in red in Figure 6) is known as the sound path length and creates that same “time-of-flight” delay to shape its gradient response.

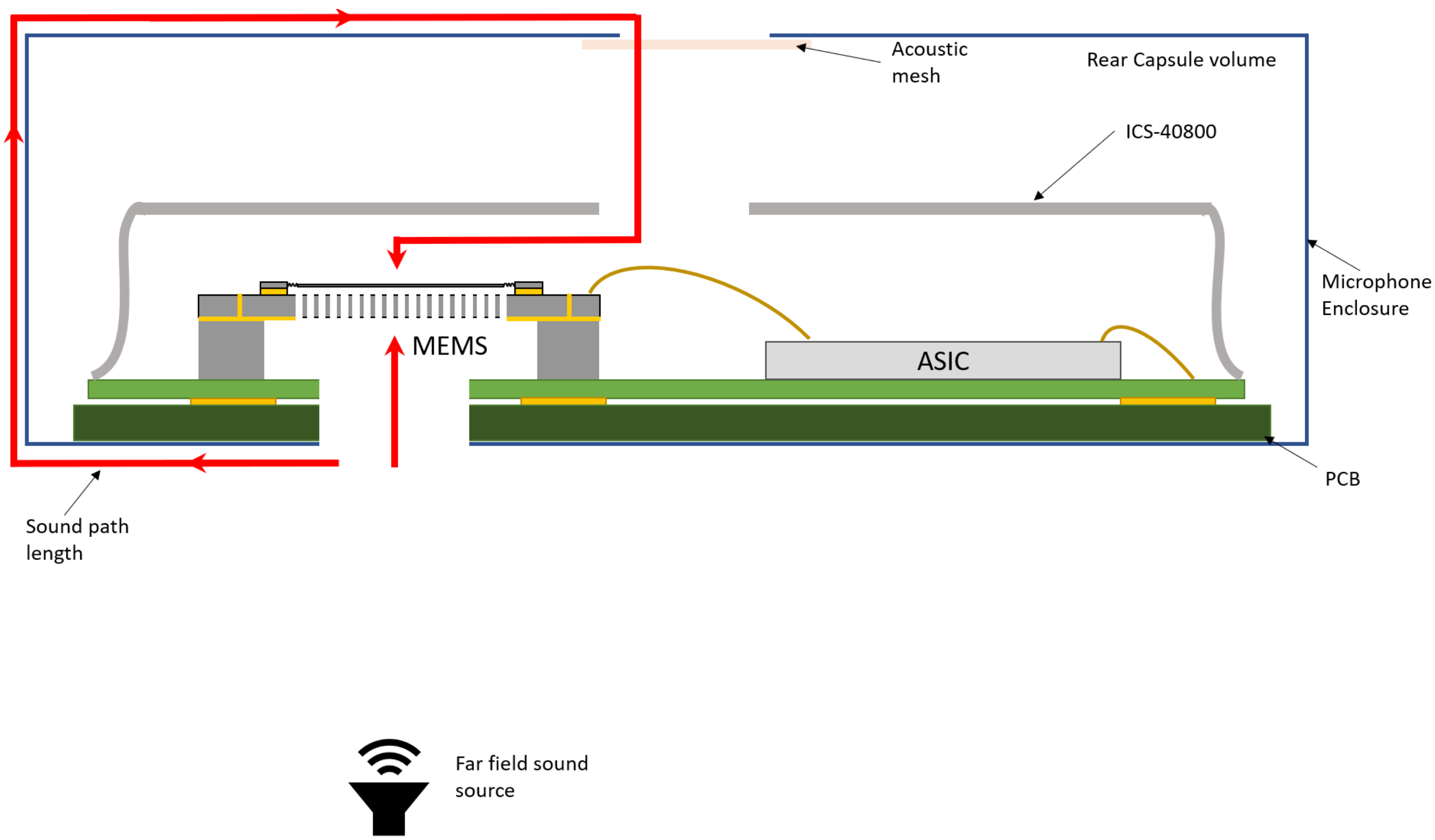

Figure 6: Sound path length of a MEMS microphone enclosed in a capsule

Figure 7 below illustrates the effects of increasing the front-to-back path length. A longer path length will yield an increased output sensitivity at low frequencies, but consequently, the first null frequency occurs earlier which means its ‘cardioid bandwidth’ would be decreased. This makes sense because it will take more time for sound to travel along the longer path length, and that increased time delay results in a larger difference in pressure, thus producing a larger signal. It’s also important to note the 6dB/octave slope at low frequencies which was mentioned earlier as a characteristic of a gradient response. The tradeoff to be made when deciding the path length is between maintaining reasonable 1kHz sensitivity (longer path length) and achieving a cardioid bandwidth to higher frequencies (short path length).

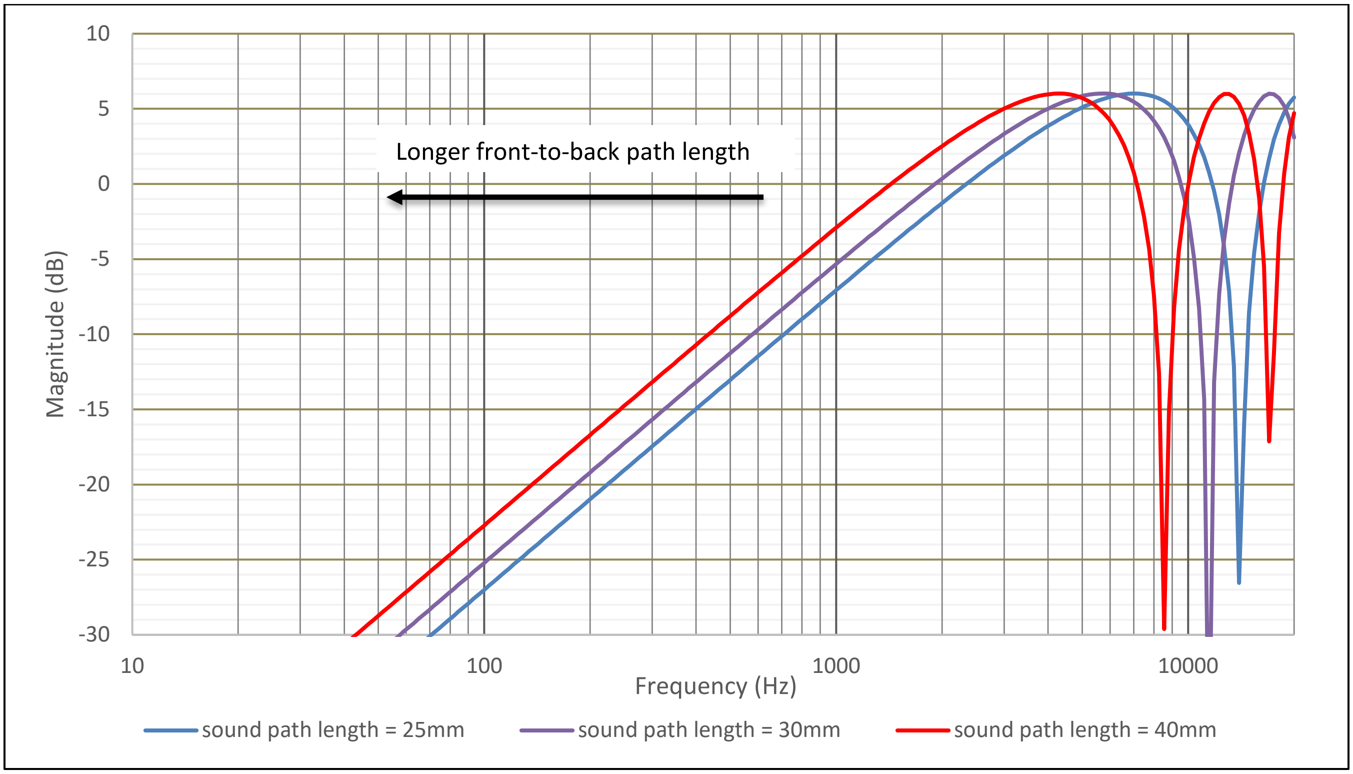

Figure 7: Effects of increasing sound path length (on-axis, 0° normalized)

Successful implementation of directional sound pickup using the ICS-40800 is application specific. It is suitable for applications such as a boom headset microphone arm where the dimensions of the housing can be designed to achieve directionality for the frequencies of interest, while it may be more challenging to implement for other applications that prohibit multiple openings in the housing. Ultimately, a lot of the challenges will depend on the system design constraints: what is the desired audio bandwidth for which a cardioid response is important and also how well the microphone can be integrated into a mechanical housing while having both top and bottom sides exposed to the desired sound source?

As the sound path length is one parameter that needs to be designed with careful consideration, another important design parameter is the acoustic resistance that is normally introduced in the sound path to the back of the diaphragm for pickup patterns other than “figure-8”. In its simplest form, this acoustic resistance is realized typically by a mesh or fabric which acts as an attenuator to only the sound pressure reaching the back of the diaphragm. Therefore, the rear lobe will become smaller than that of the pure bi-directional pattern. In fact, changing the specific resistance of the mesh and/or the area over which it is exposed will therefore vary the ratio of sound pressure reaching the front versus the back of the diaphragm at any given angle of incidence. Crucially, this rear path resistance is the main contributor in determining the resulting pickup pattern along the continuum of possible responses as shown previously in Figure 5.

Along with the rear resistance, changing the rear capsule volume and rear sound port dimensions are two other variables in determining the total acoustic filter network to sound reaching the rear of the diaphragm. Aside from determining the exact polar response pattern, this filter network allows another degree of adjustment to the upper bandwidth of the gradient response and introduces an associated frequency-dependent phase delay to the rear path. A thorough treatment of this topic is beyond the scope of this application note.

EXAMPLE APPLICATION (CARDIOID DIRECTIONAL CAPSULE)

To help illustrate the principles shown above and baseline performance, a simple cylindrical microphone capsule was designed with specific dimensions in mind to house the ICS-40800 flex evaluation board. The example application comprises of the following bill of materials:

- **1x EV_ICS-40800-FX evaluation flex board**

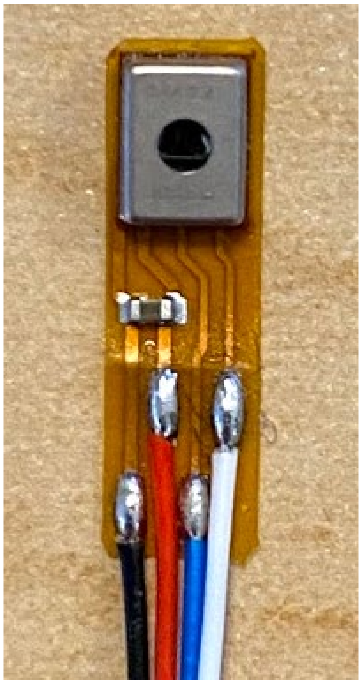

Figure 8: Top side of EV_ICS-40800-FX

Figure 9: Bottom side of EV_ICS-40800-FX

Contact your local sales representative for EV_ICS-40800-FX evaluation flex boards.

- **1x 3D printed microphone capsule**
    - **Capsule cap (rear side of microphone)**

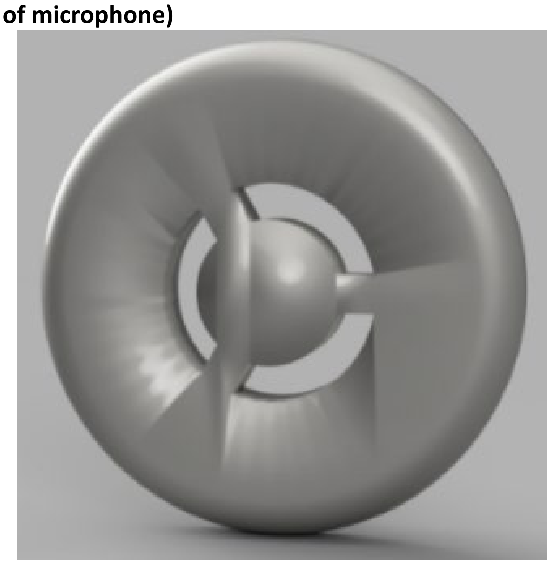

Figure 10: Rear cap of example application capsule

- **Capsule body (front side of microphone)**

Figure 11: Front body of example application capsule

The example application CAD files (.stl) can be obtained on the product page for the ICS-40800 on www.invensense.com.

- **1x Acoustic mesh**

Figure 12: Acoustic mesh fabric used to cover top sound port

The specific mesh used in this example application is the **PES 15/9 (HY) Acoustex mesh** by **Saatifil** which has a nominal characteristic acoustic impedance of 370 Rayls. Another recommendation would be the **AM 360 MKS mesh** offered by **BOPP** which has a nominal characteristic acoustic impedance of 361 Rayls.

CAPSULE ASSEMBLY

The intent with this example application is to provide end users with the CAD files so they can 3D print the model as is or tweak the design for preliminary evaluation in an alternative form factor.

The capsule body has an opening in the side wall where the ICS-40800 flex board can slide in and align with the bottom port. Once the sound port of the flex board is aligned with the front body's sound port, that should be glued in place so that the both the board is fixed to the capsule tab and the rectangular opening that the microphone goes through is well sealed.

For the capsule cap which exposes the rear side of the microphone, it is recommended to use a hole punch to cut out the mesh into a 6.35 mm (0.25") diameter circle that can be adhered to the inside of the cap with an RTV sealant to ensure a good seal around the edges, but not contaminating the exposed mesh area as that altered rear sound path impedance may produce different results.

Mating the top side of the capsule with the bottom side of the capsule will yield the assembly shown in Figures 13 and 14.

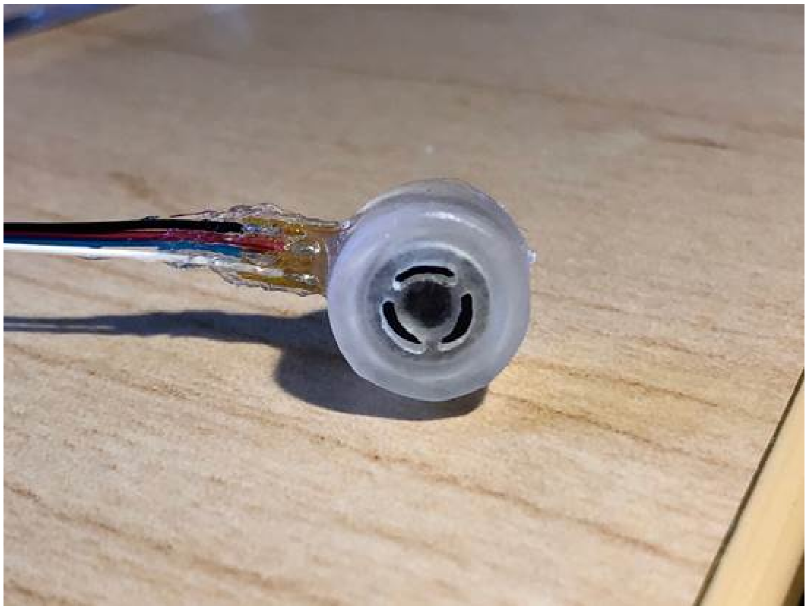

Figure 13: Rear side of assembled example application capsule

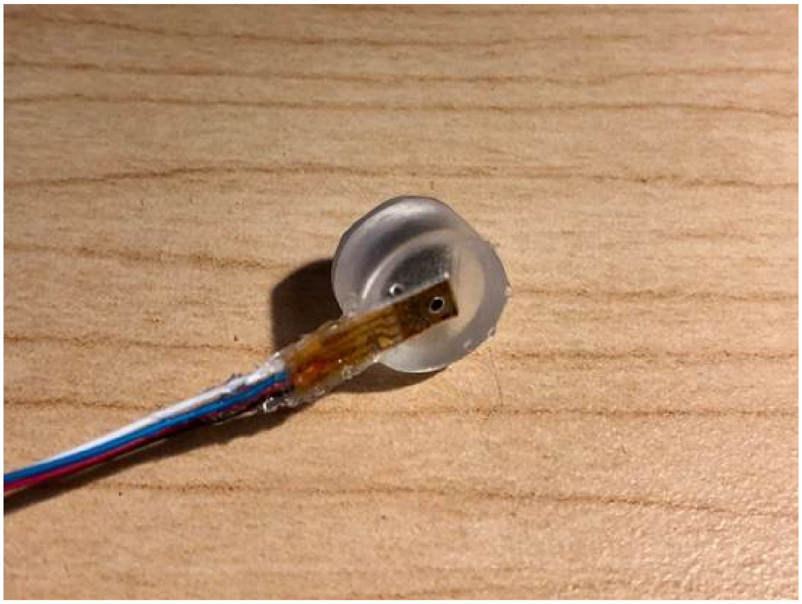

Figure 14: Front side of assembled example application capsule

POLAR PLOT AND FREQUENCY RESPONSE DATA

The following data represents the average data from five identically built example application samples. Note that 0° represents the incoming sound from the capsule body's front port while 180° represents the incoming sound from the capsule cap's rear port.

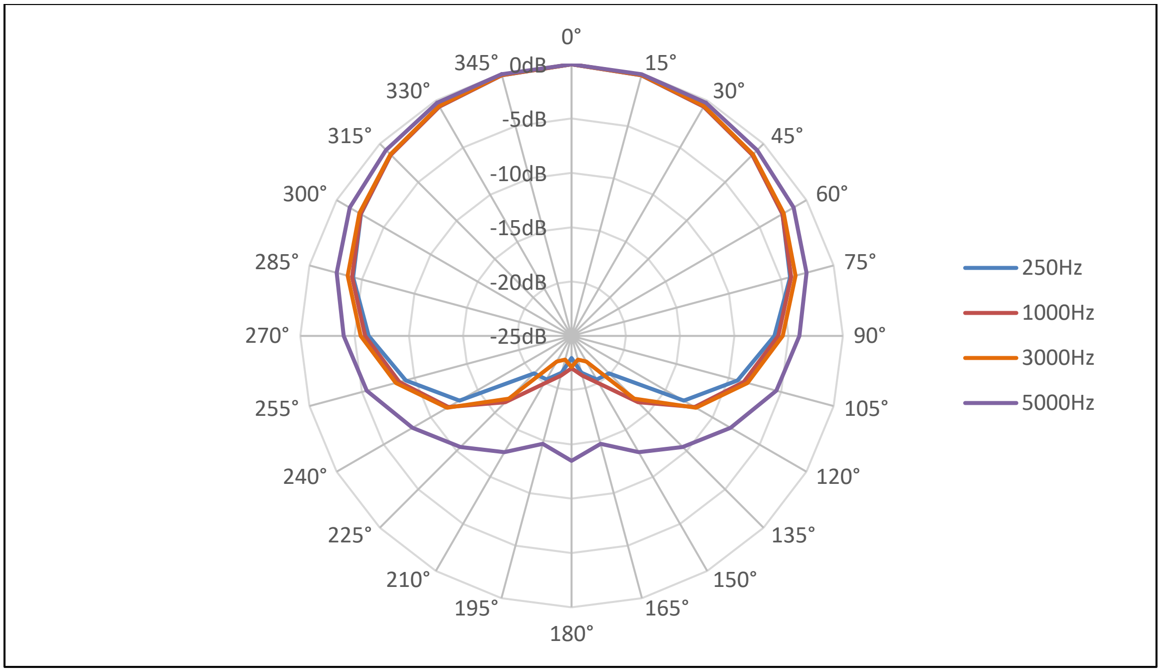

Figure 15: Typical Polar Response at various frequencies (0° Normalized)

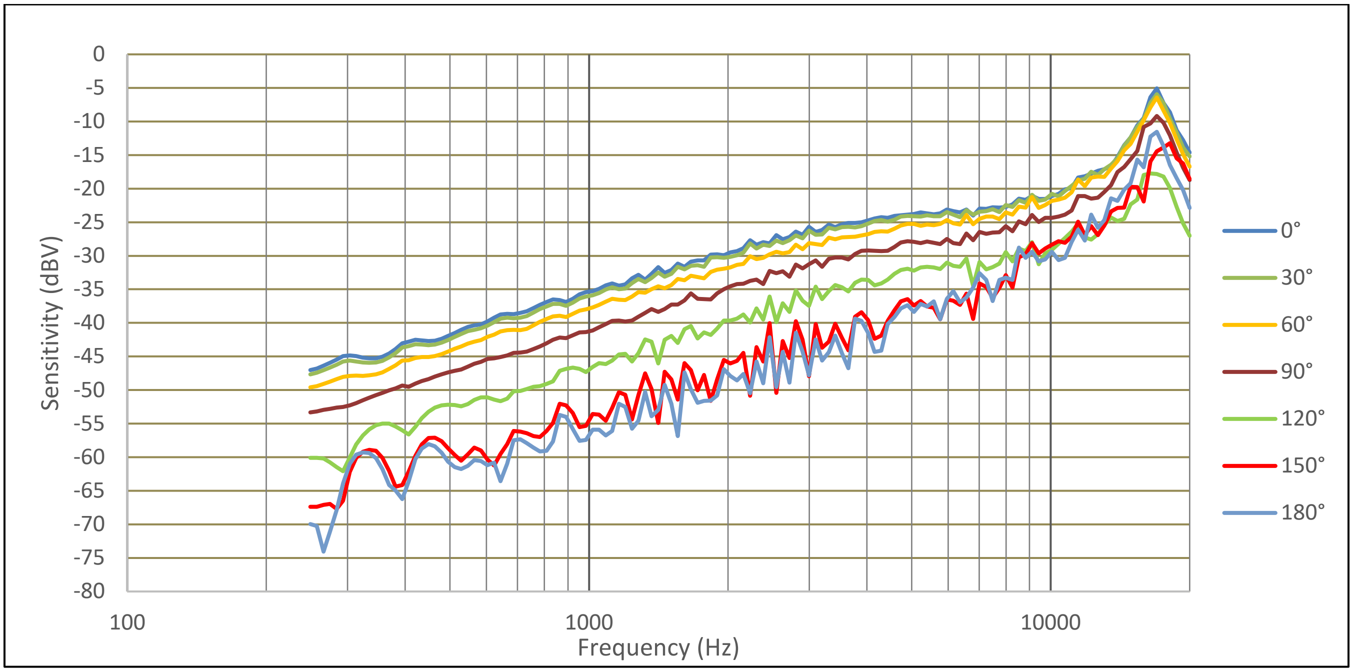

Figure 16: Typical Frequency Response at various angles of incidence

COMPENSATION CIRCUIT

As illustrated in Figure 16 and discussed earlier, when the ICS-40800 has both sides of the diaphragm exposed, the output sensitivity will be reduced at low frequencies primarily due to the fact that the sound path length will be relatively insignificant in comparison to the long wavelength of low frequencies. The sensitivity rises at about +6dB/decade as the wavelength gets smaller and smaller. To compensate for this reduced bass sensitivity, a simple EQ compensation circuit can be added to the output of the microphone to adjust the sensitivity which helps achieve a more favorable flat response. Depending on the specific system application interface, a DSP EQ can also be implemented in lieu of the analog circuit below.

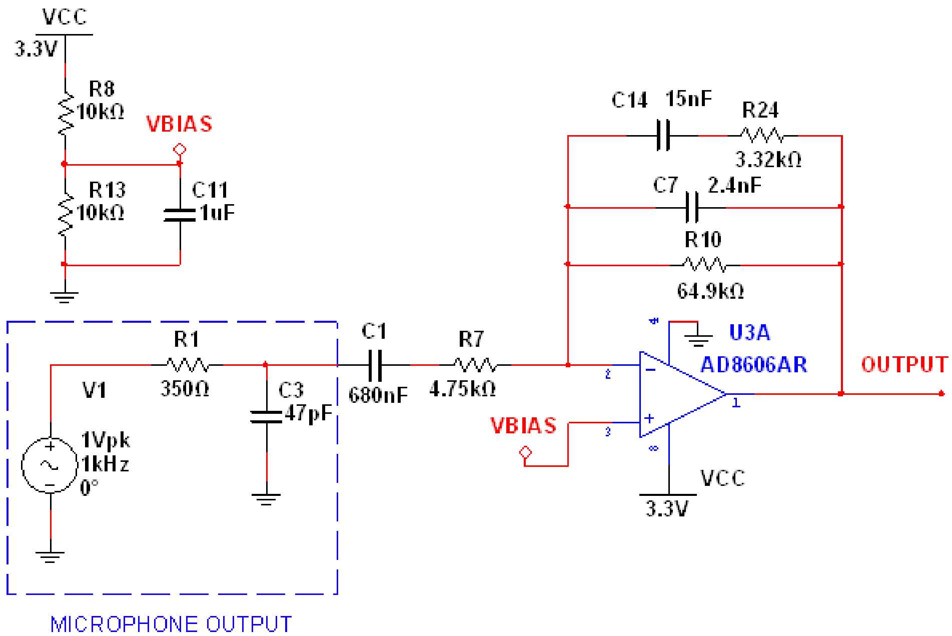

Figure 17: Discrete solution EQ compensation circuit

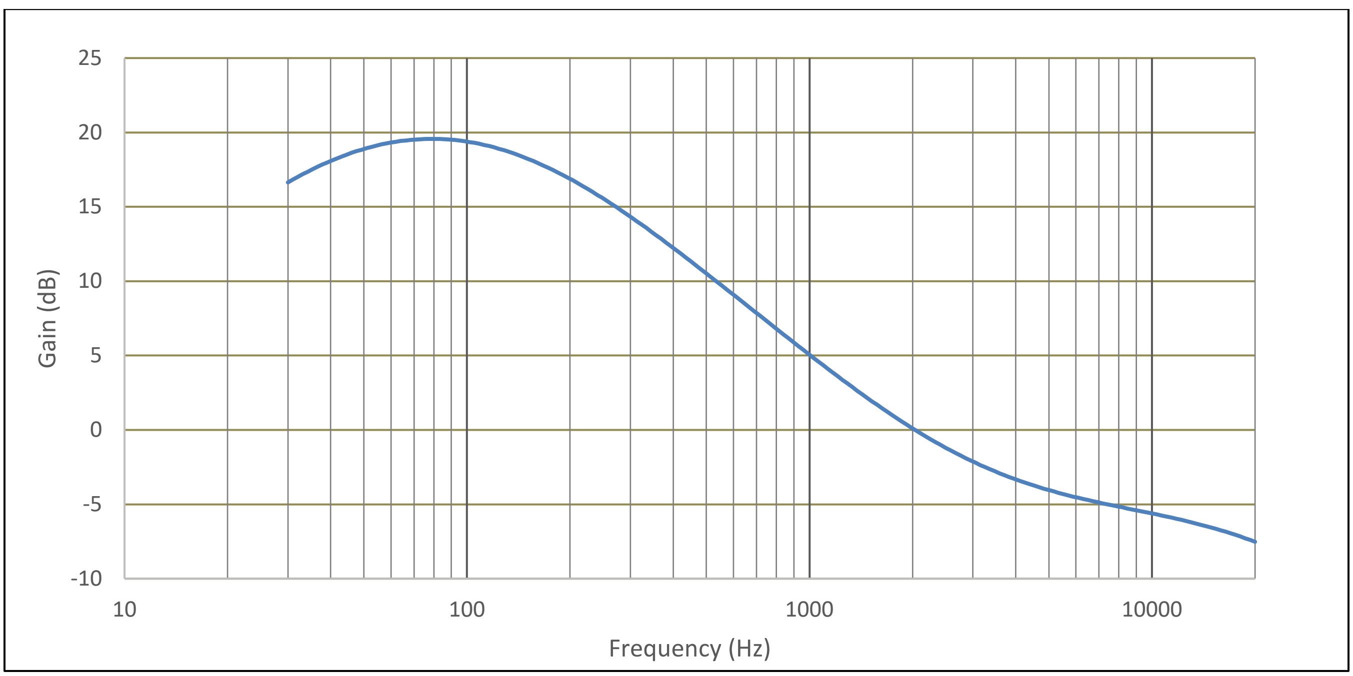

Figure 18: Recommended compensation response for example application

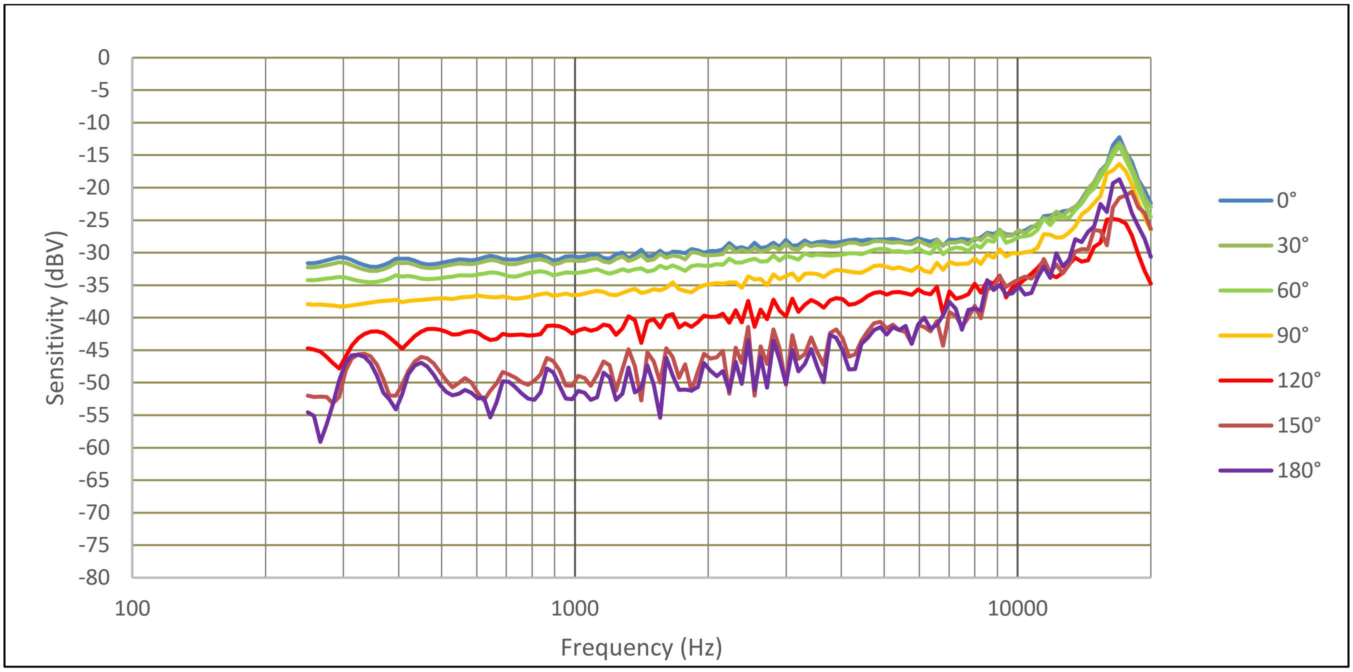

Figure 19: Typical Frequency Response with compensation at various angles of incidence

From Figure 19 above, it's apparent that as much as ~25dB of rejection can be achieved against sound originating from the rear side of the microphone capsule.

MANUFACTURING AND ASSEMBLY RECOMMENDATIONS

As mentioned in the ICS-40800 datasheet, the top port of the microphone is sealed with a heat resistant polyimide tape to prevent particle contamination prior to assembly. The protective tape size is 1.6 x 1.6 x 0.025 mm. Inner diameter of SMT nozzle is recommended to be smaller than the size to prevent vacuum leakage.

Since the cover tape has a high heat resistance, it is essential to leave the tape in place during solder reflow and recommended to remove the tape after all assembly processes. Once final product has been assembled, the cover tape should be removed with tweezers or adhesive tape with a peel adhesion rating of 10N/25mm. Do not apply a vacuum or air/liquid clean after the cover tape has been removed.

Figure 20: Top port of ICS-40800 with tape cover

APPLICATIONS SUPPORT

For China customer application support questions and inquiries, please contact techsupport_china@invensense.com.
For Europe customer application support questions and inquiries, please contact techsupport_europe@invensense.com.
For Japan customer application support questions and inquiries, please contact techsupport_japan@invensense.com.
For North America and all other region customer application support questions and inquiries, please contact techsupport_northamerica@invensense.com.

SUMMARY

The ICS-40800 is the first product of its type capable of achieving exceptional SNR by spatial sensitivity to the incident acoustic signals. Of course, the concept of SNR becomes a more complex system-level consideration than with an omnidirectional implementation. Since the desired signal in a directional application will be on-axis (0 °), the sum total of diffuse-field ambient noise (the undesired signals) will tend to be rejected by some ratio with respect to the on-axis signal according to the pickup pattern. This ratio can be measured or calculated across frequency and is known as the Directivity Index (DI). A cardioid response, for example, can theoretically have a maximum DI of 4.8dB. While the gradient response compensation EQ will tend to boost noise at low frequencies, the Directivity Index and specific off-axis rejection of the chosen pickup pattern can achieve a much higher 'effective SNR' in the application than what would be otherwise achievable by a simple omnidirectional microphone implementation.

With the proper mechanical and acoustic enclosure design, the appropriate delay paths and filtering through which the sound waves travel can be set to yield anything from a subcardioid to a hypercardioid which can achieve excellent results when it comes to directional sound or voice pickup. The directionality continuum of the ICS-40800 varies anywhere from omnidirectional to bi-directional (or "figure-8"), and by varying the exposure of the back of the diaphragm to the ambient environment, virtually any polar pickup pattern can be achieved along that continuum.

The TDK ICS-40800 example application was created with the intention of providing customers with a starting point for development, but as detailed throughout the application note, results will vary and it is strongly encouraged to first determine whether or not the ICS-40800 is the right solution for your design.

REVISION HISTORY

REVISION DATE	REVISION	DESCRIPTION
1/24/2020	0.1	Preliminary version
3/2/2020	1.0	Initial Release

COMPLIANCE DECLARATION DISCLAIMER

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