



APPLICATION NOTE AN-4

Directional Microphone Applications

Introduction

The inability to understand speech in noisy environments is a significant problem for hearing impaired individuals. An omnidirectional hearing aid works well in quiet situations where speech level is well above background noise level and both can be comfortably amplified for the wearer. Conversely, this omnidirectional aid provides limited benefit in loud, noisy conditions where the hearing aid user needs selective amplification of the speech signal relative to the background noise. Spectral filtering has not yet been shown to be effective in improving speech intelligibility by reducing background conversation noise. However, unwanted noise sources including background conversations and room noise can be attenuated based on their spatial location using a directional hearing aid.

Directional Hearing Aids

A directional hearing aid has a variable sensitivity to sound waves arriving from different locations around the wearer, and, when effectively designed, attenuates sounds coming from the sides and rear of the wearer relative to sounds coming from in front of the wearer. The actual benefit to the hearing aid user is hard to predict as it is influenced by both the wearer and the acoustic environment. Head and torso diffraction effects, room reflections, and

directionality variations with frequency can all reduce the effectiveness of a directional hearing aid.

Directionality in a hearing aid is a function of the microphone(s) which transduce the sound energy that reaches the aid. Two distinctly different system designs are available and have been used to create directional hearing aids. The first is based on the electrical combination of the output signals of two omnidirectional or pressure microphones. Although the concept of combining the output signals of two separate transducers was employed in the earliest directional microphones, it was impractical to physically house two microphones in an ITE or ITC aid until much more recently.

The second design generates a directional signal by combining two acoustic inputs within a single microphone cartridge. This type of directional microphone was patented in the 1930's and found practical application in directional aids in the 1970's and 1980's when sufficiently miniature microphone designs became available. Its success was limited by two factors, the difficulty of designing an effective directional hearing aid and the increased internal noise inherent in a directional microphone design. Often, the noise limitation can be overcome



by using a system which allows the user to switch between a directional microphone for noisy environments and an omnidirectional microphone for quiet conditions.

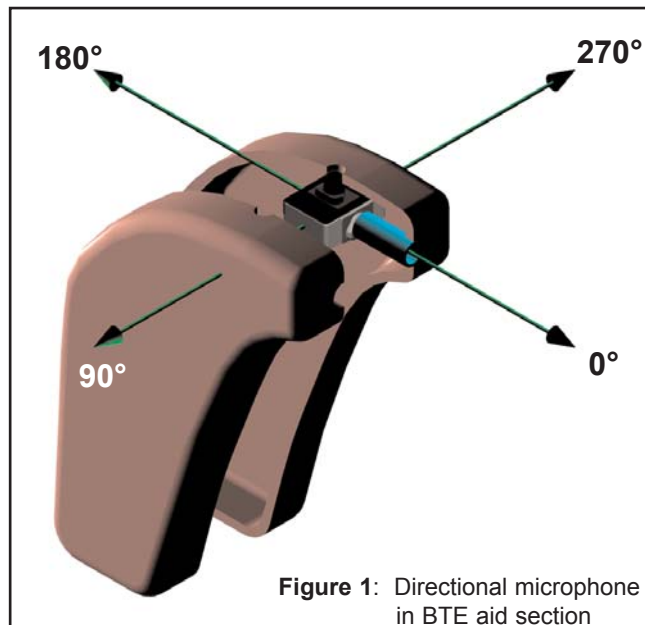
The balance of this application note will focus on the challenges faced in designing an effective directional microphone for a directional hearing aid. For a more detailed discussion and comparison of the two directional aid design options, please see references #1 through #3 in the Appendix.

Directional Microphone Design and Theoretical Performance

The simplest microphone is the pressure or omnidirectional type which provides a single opening or inlet port for sound to enter. Inside the microphone housing, the pressure generated by the acoustical signal acts on one side of a thin diaphragm, displacing it from its static position. The diaphragm movement is converted into an electrical output by the microphone. In this configuration, the microphone senses only the instantaneous acoustic pressure at its sound port regardless of where the sound source or sources are located. An ideal pressure microphone measured in a free field will thus have a polar sensitivity pattern which is a perfect circle.

In a directional pressure gradient microphone, an additional port is connected to a second opening in the microphone housing. This opening allows the acoustic signal at the second port to act on the opposite side of the diaphragm. The displacement of the diaphragm is now a function of the net difference between the

sound signals arriving at the ports. Due to the distance between the ports, the two sound signals may have different phase or amplitude relative to each other depending on the angle of incidence. A sound arriving at 90° or 270° will produce the same pressure at both ports. Since the pressure difference is zero, the microphone will have no output. Maximum pressure differences occur for sounds originating at 0° or 180° . This directional microphone's theoretical polar response pattern is a "Figure-8" with equal maximum sensitivities at 0° and 180° and equal zero sensitivity minimums, or nulls, at 90° and 270° .



In order to modify the polar response so that sounds originating at 180° are attenuated relative to those from other directions, an acoustic time delay network is introduced in the rear port. A sound wave arriving from the rear (i.e., at 180°) takes a certain additional time to travel the distance from the rear port to the front port. If the time delay network produces a delay of the

same duration, then the signal from the rear port delay network and the signal from the front port will arrive simultaneously at opposite sides of the diaphragm and cancel out each other. This results in a minimum sensitivity null at 180° and yields the familiar cardioid pattern polar response.

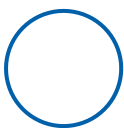


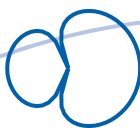

Other ratios of the internal delay of the phase shift network to the external delay of the port separation will produce different polar response patterns. Two commonly defined patterns are supercardioid and hypercardioid. Unlike the cardioid pattern which has a single null at 180°, both the supercardioid and hypercardioid patterns have a small rear lobe with nulls on either side. All of these response patterns are members of a limaçon curve family derived from the equation $f(\theta) = (1 - k) + k \cdot \cos(\theta)$ where $k = e / (e + I)$, where e is the external phase shift and I is the internal phase shift. The table below shows a comparison of some of the more important features of each polar pattern.

Directivity Index

The Directivity Index is defined as the difference in dB between the power transmitted by an omnidirectional microphone and a directional microphone in a diffuse field. The Directivity Index is a way to compare the directional benefit of different polar patterns assuming that the interfering noise arrives from all angles with equal probability. Under ideal conditions, where an ideal microphone's response conforms to the limaçon curve equation, the Directivity Index can be calculated for any value of k . A maximum directivity index of 6dB results from a hypercardioid pattern, where $k = 0.75$.

Articulation-Index Weighted Directivity Index (AI-DI)

The final step in identifying the benefits of a directional microphone for a hearing impaired user is to combine the Directivity

	Omni	Cardioid	Supercardioid	Hypercardioid	Figure-8
Polar Pattern					
Delay Ratio, K	0	0.5	0.63	0.75	1.0
Null Angle(s)	--	180°	±125°	±110°	±90°
Directivity Index, DI	0 dB	4.8 dB	5.7 dB	6.0 dB	4.8 dB



Index at a given frequency with the speech energy that will be at that frequency. This is accomplished by calculating an Articulation-Index weighted Directivity Index based on the Articulation Index developed by Bell Telephone Laboratories to characterize the performance of communications systems. The result provides a single value summary of the expected benefits of a given directional microphone design.

Real World Performance

The preceding discussion has assumed an ideal directional microphone in an ideal environment. However, it is important to consider the factors which limit directional microphone systems in actual use.

The directional microphone's sensitivity and polar response vary with frequency. At low frequencies, where acoustic wavelengths are far greater than the port separation distance, the phase differences between the signals at the two ports become exceedingly small. Thus, the sensitivity of a directional microphone falls off more rapidly at low

frequency than an omnidirectional microphone, resulting in a relative increase in the internal noise of the directional microphone.

The acoustic filter characteristics of the front and rear inlets, including the time delay network, are a function of the directional microphone's internal acoustic impedances and also vary with frequency. These internal acoustic impedances then interact with the acoustic impedance of any extension tubing used to connect the directional microphone ports to the hearing aid shell sound inlets. Even directional microphone mounting configuration can have an impact since the shape of the hearing aid shell, especially between the shell's sound inlet ports, controls the microphone's effective port separation.

All of the preceding factors will, to varying extents, degrade the polar response and Directivity Index of the directional microphone as they alter its performance away from that defined by the ideal limaçon curve. Figure 2 shows an example of the effects of these factors.

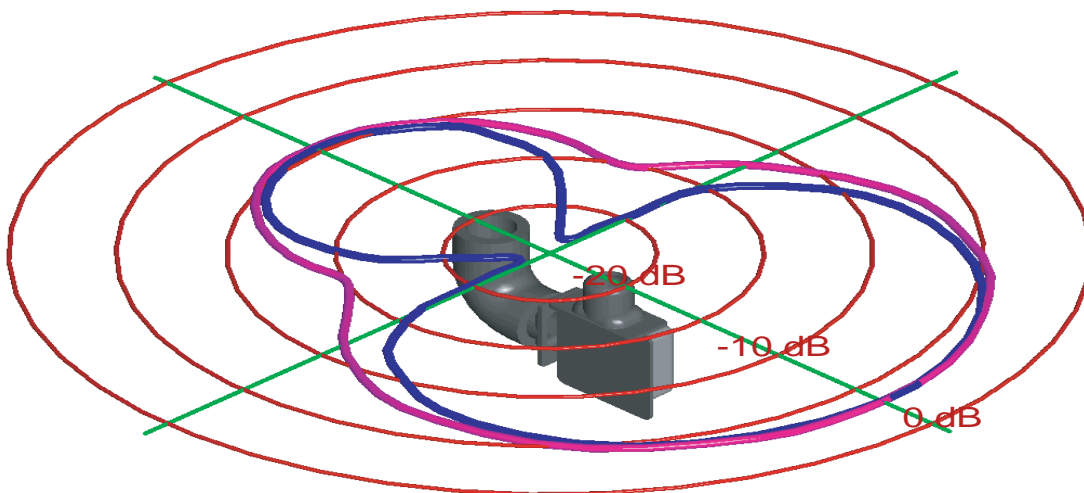


Figure 2: FP microphone measured free-field response at 2kHz (magenta) vs. ideal limaçon curve (blue)



The wearer and the listening environment also impact the performance of the directional hearing aid system. True free field conditions do not usually exist and therefore reflections of unwanted sounds appear at the 0° (front) direction mixed in with the desired sound signal. There may be standing waves or interference patterns with minima or maxima coinciding with the location of one (or both) of the sound ports. The human body in general, and the wearer's head in particular, create diffraction and reflection effects at the hearing aid shell sound inlets. These effects become increasingly significant and complex at higher frequencies as acoustic wavelengths become shorter and comparable with the dimensions of the head, ear, and smaller physical features (see Figure 3, below). Wind noise can be a significant factor as the pressure gradients caused by turbulence can be relatively large compared to acoustic pressure gradients at low frequency.

Despite all of the above effects, there are still useful directional properties that greatly benefit the wearer of a directional hearing

aid. The complexity of interactions involved preclude making meaningful theoretical calculations of aid performance so that *in situ* measurements are required to determine the directionality of the hearing aid and wearer as a complete system. Using a head and torso manikin such as KEMAR®, measurements can be made which yield the Directivity Index at various frequencies in the audio band. This data can then be weighted by the Articulation Index to derive a performance level of the system being evaluated.

Hearing Aid System Design

Designing a directional hearing aid system using the “fixed” directional microphone described above would typically begin with the determination of the sound inlet port spacing on the hearing aid shell. Using that information and the polar response pattern desired, the internal delay of the directional microphone would then be calculated. The selection of a specific microphone model could then be made based on this desired sound inlet port spacing and delay. The

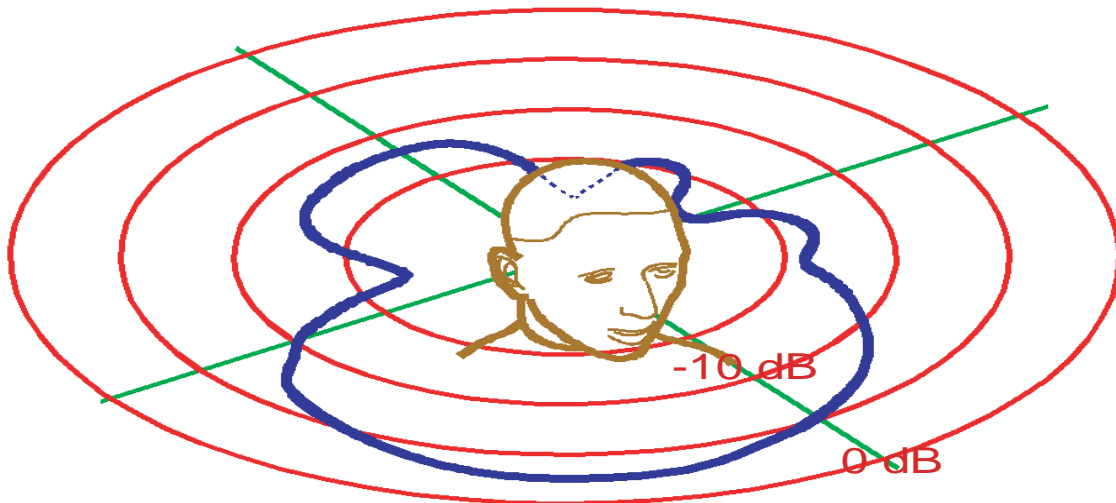
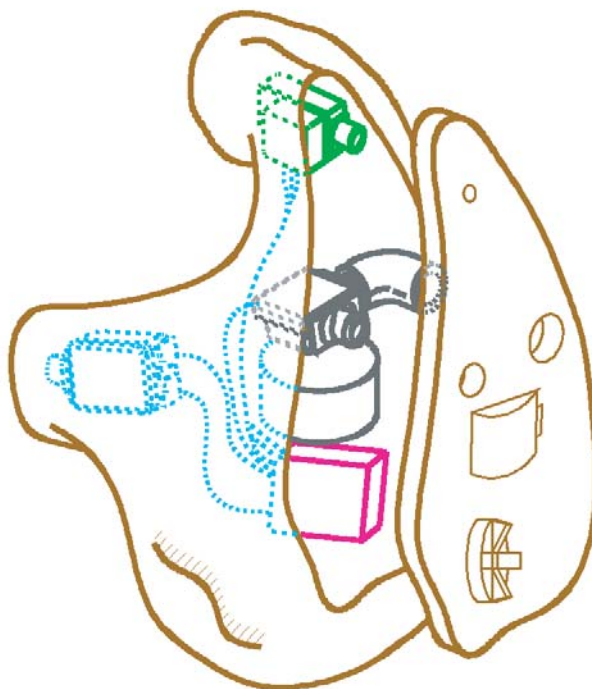


Figure 3: FP microphone, in ITE hearing aid, response at 2kHz measured *in situ* on KEMAR manikin.

hearing aid system design must be validated by *in situ* measurements on KEMAR®. Design changes for improved directionality may be implemented by altering the internal delay of the directional microphone, modifying its polar response towards the desired polar response characteristics.

Knowles Electronics is committed to working with hearing aid manufacturers throughout the design process to ensure that the directional microphone can provide optimum directionality and response in each specific hearing aid application.



Appendix: Additional References

Multiple omnidirectional microphone cartridges as directional microphones:

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2. "Application of Multiple Microphones in Hearing Aids", *Knowles Electronics Application Note*, S-911-0897
3. Thompson, S., "Directional Patterns Obtained from Dual Microphones", *Knowles Electronics Engineering Report*, October 1997

Fixed directional microphones:

1. Bauer, B., "Microphone Directivity", *Transactions of the IRE-PGA*, July 1952, 10-20
2. Valente, M., *Hearing Aids: Standards, Options, and Limitations*, 1996, 142-144
3. Madaffari, P., "Directional Matrix Technical Report", *Knowles Electronics Engineering Report*, 1983

Directivity Index:

1. Bauer, B., "Microphone Directivity", *Transactions of the IRE-PGA*, July 1952, 10-20

Articulation-Index Weighted Directivity-Index:

1. Roberts., M. & Schulein, R., "Measurement and Intelligibility Optimization of Directional Microphones for Use in Hearing Aid Devices", *103rd AES Convention*, 1997

Real-world performance and measurement:

1. Preeves, D., "Directional Microphone Use in ITE Hearing Instruments", *The Hearing Review*, July 1997, 21-27
2. Killion, M., et. al., "Real-World Performance of an ITE Directional Microphone", *The Hearing Journal*, April 1998

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NOTE: Specifications are subject to change without notice. The information on this Data Sheet reflects typical applications. Specific test specifications defining each model are available by requesting Outline Drawing Sheets 1.1 and Performance Specifications Sheets 2.1 of that model number. Knowles' responsibility is limited to compliance with the Outline Drawing and the Performance Specification application to the subject model at time of manufacture.

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