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Directional Matrix Technical Report
Project 10554

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Directional Matrix Technical Bulletin

Section 1 Problem Statement

Directional hearing aids account for a significant portion of all aids supplied to the hearing impaired. The process of designing such an aid has been in some instances a costly and time consuming process. This bulletin was written to help the hearing aid manufacturer in the process of choosing a suitable directional microphone cartridge for a directional hearing aid and, hopefully, to help solve some of the problems associated with designing a directional hearing aid. It will illustrate some approaches that were tried as well as some of the results that might be expected. This approach is based on the versatility of the series of microphones in the new Directional Matrix.

In designing a directional hearing aid two of the possible routes that can be taken are:

1. The hearing aid case can be designed to work with a specific directional hearing aid microphone cartridge.

2. The directional hearing aid microphone cartridge can be selected that best works with the proposed hearing aid case design.

The series of directional hearing aid microphone cartridges is intended to provide guidance in the first approach and to make the second approach practical.

The purpose is to be able to choose a directional microphone cartridge from a series, one of which should perform as well as a custom design. This will not be the case if there are too few models to select from or if the characteristics of these microphone cartridges are too similar i.e. they do not span the useful range needed for practical directional hearing aids. The directional microphone cartridges comprising the Directional Matrix were designed to make the selection easier. The series was designed as a whole and the models in the series were chosen so as to span the range of time delay and mechanical configurations now used in directional hearing aids.

Section 2 Necessary Physics

It would be best at this point to define a few terms and review some directional microphone theory. As used in this report the polar pattern is a measure of a microphone's response to sound as a rotation is performed around a vertical axis. The openings in the hearing aid shell or microphone housing where the sound is sampled will be called ports. If the directional microphone is measured in isolation, positioned as if the device were being worn, and the rotation axis passes through the microphone, the zero degree orientation is with the sound ports aligned in the vertical plane containing the sound source and the rotational axis.

"In situ" is a term used often in this report. It means literally " in place" and describes the situation where the hearing aid is worn by a test subject. If measured in situ, zero degrees is with the wearer facing the sound source, and the axis of rotation is an imaginary line through the top of the wearers head. The test "wearer" used to obtain this data was the KEMAR® manikin.

A gradient microphone is a microphone which samples a sound wave at two points in space usually close to each other. There are different types of traditional first order, gradient microphones, each having a different polar response pattern when measured in isolation in an anechoic room. One such geometric pattern with a single null at 180 degrees is a cardioid. A microphone producing this polar pattern is then termed a cardioid microphone. This pattern is one member of the limacon family. The limacon family is based on the formula:

$$S = N \times (A \times C + B \times \cos\theta)$$

S is the signal strength, measured when the microphone has been rotated through the angle θ away from the sound source. A is the delay of sound internal to the microphone. C is the speed of sound and B is the distance between ports. N is a normalizing factor. A form more easily used can be derived from the above formula by dividing by the factor N x A x C and redefining S/N x A x C as S'. The new formula is:

$$S' = 1 + R \times \cos\theta$$

R is defined as B/(A x C), the ratio of the maximum time it will take sound to travel from one port to the other to the internal time delay. This external travel time will be called the external time delay. The cardioid condition occurs when the port spacing B equals the speed of sound C times internal delay A, or in other words when R equals one. Other patterns shown in the literature are formed when this ratio is the square root of three or three itself. The representative equations are then:

$S' = 1 + \cos\theta$ cardioid

$S' = 1 + (\sqrt{3}) \times \cos\theta$ supercardioid

$S' = 1 + 3 \times \cos\theta$ hypercardioid

For R equal to one there is a null at 180°. If R is less than one a minimum will occur at 180°, but it will not be a true null. For values of R greater than one there are two symmetric angles where nulls occur. The figures just mentioned can be made to apply to a hearing aid measured in isolation.

There have been various opinions as what is the best choice for R, i.e. what is the best ratio of maximum external delay to internal delay. No matter what citerion is used, either the external spacing of the hearing aid case or the internal delay of the directional microphone cartridge used, or both may be changed in the attempt to meet that condition.

The practical result of the application of these equations to a microphone is one whose sensitivity is reduced for sounds originating from directions other than directly forward. The 0° referent is the direction the hearing aid and the wearer are facing. This is assumed to be the favored direction for listening. Normally the unwanted sounds arrive from some other direction (usually in the rear hemisphere).

A directional microphone cartridge, as used here, is a component of a directional hearing aid. For the cartridge, the internal delay is fixed but the port spacing is set by the hearing aid housing. The value of R is not defined for the cartridge. Consequently the same directional microphone cartridge could be made into a cardioid, supercardioid or hypercardioid microphone, with the proper choice of port spacing.

Another topic necessary for a discussion of directional effects in the real world is diffraction. Diffraction effects cause the major problems in transition from the above theoretical equations to actual application. Diffraction occurs when the path of a sound wave is obstructed by an obstacle. The smooth flow of the sound waves is interrupted by the object and the perturbations that occur will cause the actual measurements to be distorted versions of the theoretical values. For an isolated hearing aid, the principal effect is that the sound waves follow the outline of the case rather than move in a straight line. The net result for a directional microphone is that the apparent spacing between the two ports has been increased over a simple straight line, point to point measure. This increase depends on the frequency of the sound wave and the exact contour of the shell. The length of a string stretched between the effective locations of the two ports, supported by the shell's contour, is a useful approximation. Hence the term "string length". The effective location of a port is approximately one radius of the port, outside of the port. This concept of "string length" is useful in extending the theoretical concepts to actual applications. Some judgement is involved as it is possible to propose a configuration where such a rule is obviously not applicable.

There are diffraction effects caused by the human body. They cause apparent changes in both the speed of sound and the wavelength of a sound wave. These effects are a function of the location of the measurement point, the direction from which sound is arriving, and the frequency of the sound wave. For a position just above the ear, with the sound coming from the rear, and in the middle of the frequency range transmitted by hearing aids the apparent speed of sound is about 20-30% slower than in an undisturbed field and the measured value of a wavelength is similarly reduced. The result is that physical port spacings appear to be increased by a factor of 1.2 to 1.4 when the aid is worn by a person or suitable manikin.

Section 3 Directional Matrix

The directional microphone cartridges in this series differ principally in their internal time delay. This is an acoustic and not mechanical difference so that representitives of the four available time delays will appear outwardly identical and may be physically interchanged in a hearing aid housing. This ease of substitution is one of the useful qualities of these directional microphone cartridges. The directional cartridges used in this illustration share the same physical appearance, the one to the left in Figure 1. As Figure 1 shows this is only one of several configurations that could have been used. The results should be independent of the actual microphone cartridge configuration. The Directional Matrix consists of the combinations of these time delays and case configurations.

The hearing aid output, being a result of the acoustic parameters of the directional cartridge and the mechanical layout of the hearing aid shell, will vary from cartridge model to cartridge model and from hearing aid case design to hearing aid case design, in a predictable pattern. With a given microphone cartridge the directional properties can be changed by alterations in the shell, chiefly in the spacing between the two port openings. A similar result can be achieved with a fixed case design by changing the microphone cartridge and hence the time delay. It is this latter property that makes the matrix versatile.

The internal time delays of the directional cartridges comprising the matrix were chosen with several criteria in mind. First of all it was decided that the variation in internal time delay should form a geometric rather than an arithmetic series. Polar patterns are dependent on the ratio of time delays and spacings, which makes a geometric series suitable. Another goal, was that some of the cartridges in the series should incorporate internal time delays familiar to hearing aid designers.

Previously it was noted that three of the traditional polar response patterns do form a geometric series in which R, the ratio of maximum external delay to the internal delay varies as the square root of three. With the value of internal delay chosen, a hearing aid case could be built with the external port spacing to provide an external delay of the same value. This would form a cardioid pattern when measured in isolation. If a second microphone were built having a time delay $1/(\sqrt{3})$ shorter and a third having a delay $1/(\sqrt{3})$ shorter still, the second would have a supercardioid response and the third a hypercardioid response.

It seemed logical to adopt the square root of three then as the geometric factor relating the internal time delays of the microphone cartridge. However this seemed too great a step. To provide an intermediate value in a geometric series, the square root of the original multiplicative factor is used. This is the square root of the square root of three or the fourth-root-of-three. A familiar pattern would now occur with every other step in the series.

We have established a series of time delays that fit the fourth-root-of-three ratio pattern and coincide with time delay values that have been found useful in practice. They are: 56.8, 43.2, 32.8 and 24.9 microseconds.

Section 4 Shell Design

Over the years a "rule of thumb" procedure has evolved to aid in the design of directional hearing aids. As an illustration of that procedure and what might be expected from using it, four simulated hearing aid shells were constructed. A polar response pattern with a minimum at 180° in situ was the initial objective. To achieve this the theoretical equation for a directional microphone was used with some modifications for diffraction.

We have previously shown that to have a minimum at 180°, R has the value 1. Since R equals B/(A x C), we then have:

$$B = A \times C$$

In situ, because of diffraction, the apparent speed of sound has been slowed by a factor of .7 to .8 so that the condition for null could be written as

$$B = A \times (.738 \times C)$$

where C is 34400 cm/sec., the speed of sound in free air. For the cartridge with a delay of 56.8 microseconds the calculated string length is then 1.44 cm. or .568". We have taken the liberty of using .738, as it lies near the geometric mean of .7 and .8 and provides a memory aid: the time delay for a null at 180° in situ is approximately the string length in hundreths of and inch.

We can require that the remaining three hearing aid shells when matched to a respective directional cartridge should also produce a minimum at 180° when measured in situ. Because of the last equation above and because the time delays form a geometric series the string length of the hearing aid shells will do likewise. The values for the string length are then, .568", .432", .328" and .249". Any value within ±10% of these values would result in a similar appearing polar pattern.

It is somewhat of a fortuitous coincidence that the inverse of the factor .738 used in the last equation is approximately the fourth-root-of-three. If a hearing aid case used to produce a minimum at 180° in situ, is used with a cartridge whose internal delay is one step lower in the series, the new combination should produce a near cardioid pattern when measured in isolation. The converse should also hold true.

For the purpose of this illustration, an add on part in the form of a tunnel was adopted to achieve the required port spacing for three of the hearing aid shells. Except for this tunnel and the diameter of the duct work used to connect the cartridge openings to the hearing aid ports, the hearing aid shells were identical. This allowed each hearing aid shell to be modified easily and quickly to achieve any one of four string lengths without disturbing the directional cartridge. The constructs used for this report are shown on Figure 2.

The directional properties are affected by the design of the duct work leading from the microphone cartridge through the hearing aid shell to the outside world. This includes both front and rear ports. At the rear both the tunnel opening and port tubing diameter were made as large as seemed feasible. This is a primary design rule . Constrictions are to be avoided unless absolutely necessary. To compensate for inertance at the rear port it was necessary that the inertance at the front port be adjusted. In normal practice this will probably alter the high frequecy sensitivity. Therefore there may be a trade off between the frequency response pattern and the polar response pattern. The effect of inertance is primarily seen at the higher frequencies, above 1 kHz. If the directivity begins to fail for a band of frequencies (not just a spot frequency), then the balance of inertance between the front and rear port should be checked.

Section 5 Measurements and Results

As mentioned earlier the external delays of the four hearing aid shells and internal delays of the four directional cartridge models belong to separate geometric series based on the fourth-root-of-three as the ratio between adjacent elements. A matrix would then be formed using the internal delays of the microphone cartridge and the spacings of the hearing aid ports as coefficients. The matrix so formed would contain 16 elements, each element composed of a selection of one microphone cartridge and one aid shell.

The data shown in Figures 3-6 are the polar patterns measured for the 16 possible configurations. Three 1/3 octave bands of noise, centered at 1.0 kHz, 1.6 kHz and 2.5 kHz, were used as the stimulus. The use of this narrow band noise averages out effects that are highly sensitive to anechoic room quality or exact hearing aid placement. For each page, a single hearing aid shell was used and the measurements reflect the progressive change in time delay as each directional microphone cartridge was substituted. The upper row is the response measured on a manikin, while the lower row reflects the same hearing aid shell and microphone cartridge measured in isolation.

Other useful data are the more conventional frequency responses. The characteristics of a directional microphone differ from a conventional pressure microphone in that the output rises at 6 dB per octave frequency for a constant amplitude input. This property in itself is sometimes useful as variations of pressure microphones with this type of frequency response are also in use today. The increase in sensitivity with frequency is a consequence of the method of obtaining the directional performance and is a general property of this type of first order gradient microphones.

Figures 7-10 show the zero degree frequency response characteristic. Also shown on each chart is the 180° response characteristic. Where the internal time delay matches the external time delay, with diffraction taken into account, the 180° response is considerably attenuated compared to the zero degree curve. Where the internal delay is less than the external delay there will be two angles at which the delays are equal. They will be symmetric for hearing aids measured in isolation, but the asymmetry resulting from placement over the ear of the wearer will in general distort the effects. If the polar response patterns showed appreciable attenuation at an angle other than 180°, then the frequency response characteristic at this angle was also shown in Figures 7-10.

Section 6 Interpretation of Results

As shown on Figure 11 the same hearing aid case can be used to produce a cardioid appearing response in both isolation and in situ. To do this a shell is used which produces a cardioid response with one of the directional microphone cartridges when measured in isolation. The microphone cartridge with the next higher time delay when used in the same hearing aid shell should produce a similar pattern in situ, in that the sensitivity declines to a minimum at about 180°. Another interesting feature can be seen in the top row of Figure 6. For the polar patterns shown, the string length of the hearing aid case was less than that required to produce a minimum at 180°. However minima were recorded at approximately 225 degrees. The polar patterns also appear to have maxima at about 45 degrees or 180 degrees from the minima. Some of the polar patterns on the other figures also show this effect. It is not predicted by the simple theories used so far, and is probably due to "head shadowing", a condition which occurs when the head is between the hearing aid and the sound source.

Pressure or single port hearing aids also have directional properties when measured in situ. For a hearing aid using a single port pressure microphone the maximum would appear at about 90 degrees and the minimum at about 270 degrees. For a directional hearing aid a shift of about 45 degrees toward the front has occurred in the directional pattern. In difficult listening conditions the hard of hearing will frequently turn so that their better ear faces the speaker in order to improve the signal to noise ratio. It is then difficult to both listen to and look at the speaker. With a directional aid it is easier to do both.

For directional hearing aids where the effective external delay is less than or equal to the internal time delay, in general a single minimum occurs. When the external delay exceeds the internal delay two minima would be expected from simple theory. For in situ measurements triple local minima can sometimes be observed with the intermediate one lying at about 225 degrees. Again, head shadowing apparently causes this effect.

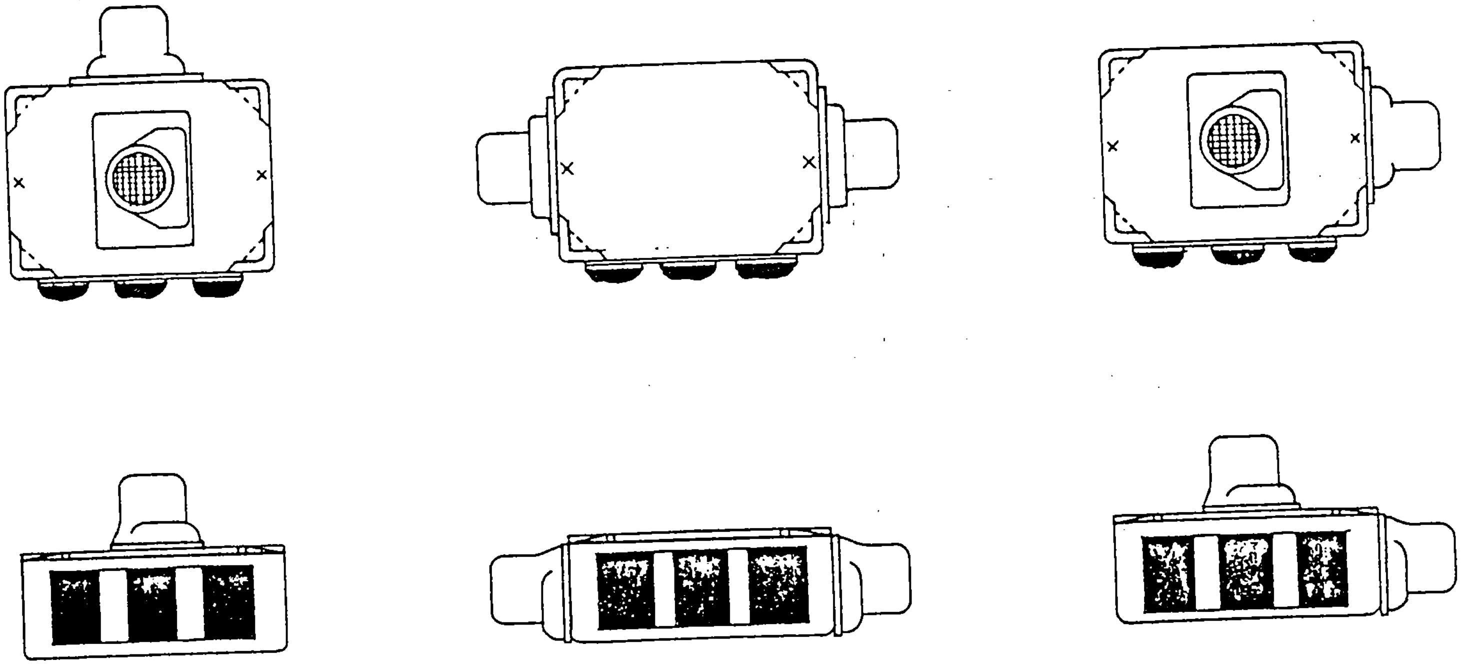
Figure 12 shows how it is possible to achieve a change in polar response pattern by changing either the hearing aid case or the directional microphone cartridge. The entries in the last column are identical, with delay of 24.9 microseconds and a physical spacing of .568 inches (measured as string length). Proceeding to the left each entry in the top row corresponds to an increase in internal delay by the factor the fourth-root-of-three. In the lower row proceeding to the left, each entry corresponds to a decrease in port spacing again by the factor the fourth root of three. The ratio of internal delay to port spacing is therefore constant in each column even though the values for port spacing and cartridge internal delay were different. As long as this ratio is the same the polar patterns will be similar.

Section 7 Conclusions

Hearing aids measured in isolation behave in an easily calculable fashion. With any given directional microphone cartridge it is possible to design the case so as to achieve any directional pattern in the limacon family. It is necessary that the port spacing have the proper value.

It is possible to extend theory to the same hearing aid measured in situ, but only if a broad interpretation of the polar pattern is allowed. There is an apparent increase of port spacing by a factor of about 1.3. This can be offset so that the polar responses measured in situ and those measured in isolation will appear similar if a microphone cartridge with a factor of 1.3 greater time delay is used for the in situ condition.

While the polar response patterns in situ do not fit a simple equation, the simultaneous scaling of external port spacing and internal delay show little change in response shape. With directional microphone cartridges available having different internal delays, it is possible to change the polar response pattern without an appreciable change in hearing aid design.



Port Designation

12S/OJP

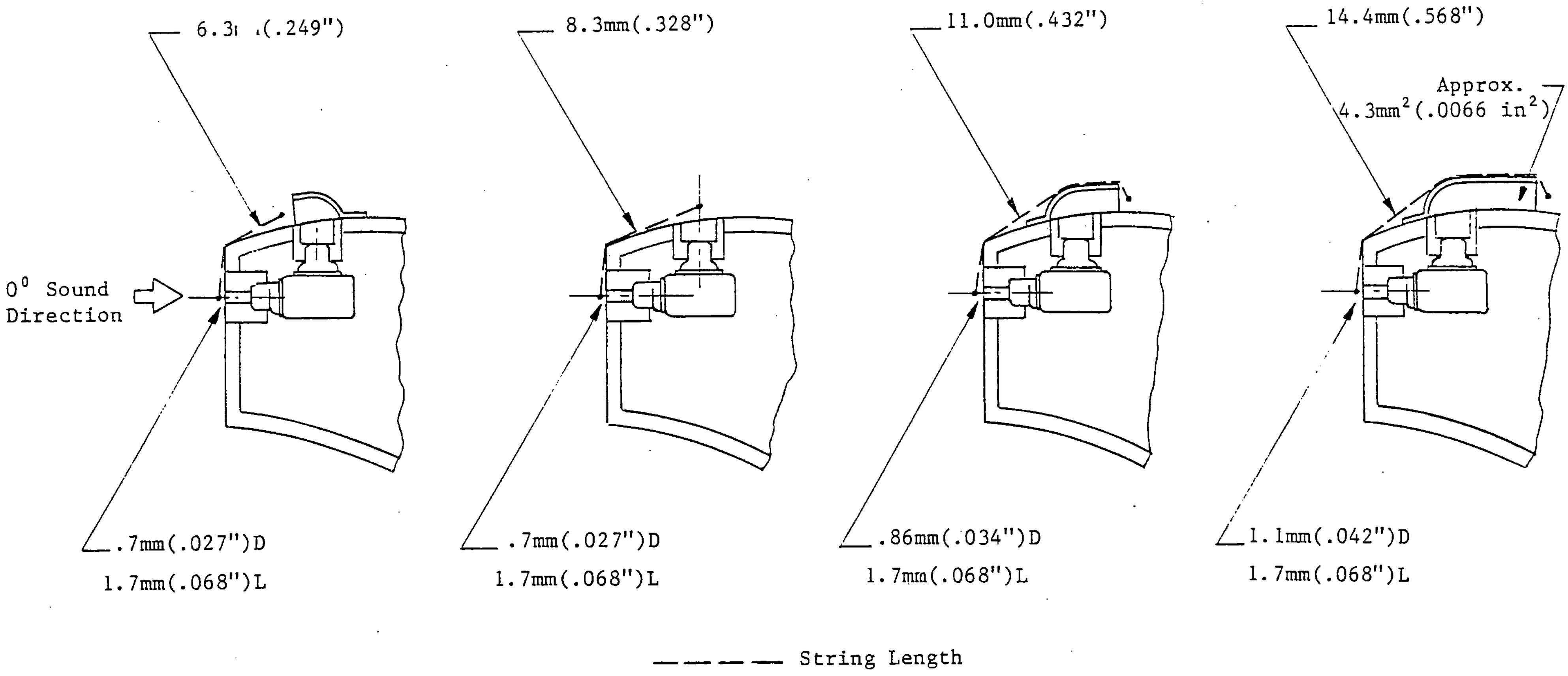
3S/9S

3S/OJP

PHYSICAL CONFIGURATIONS

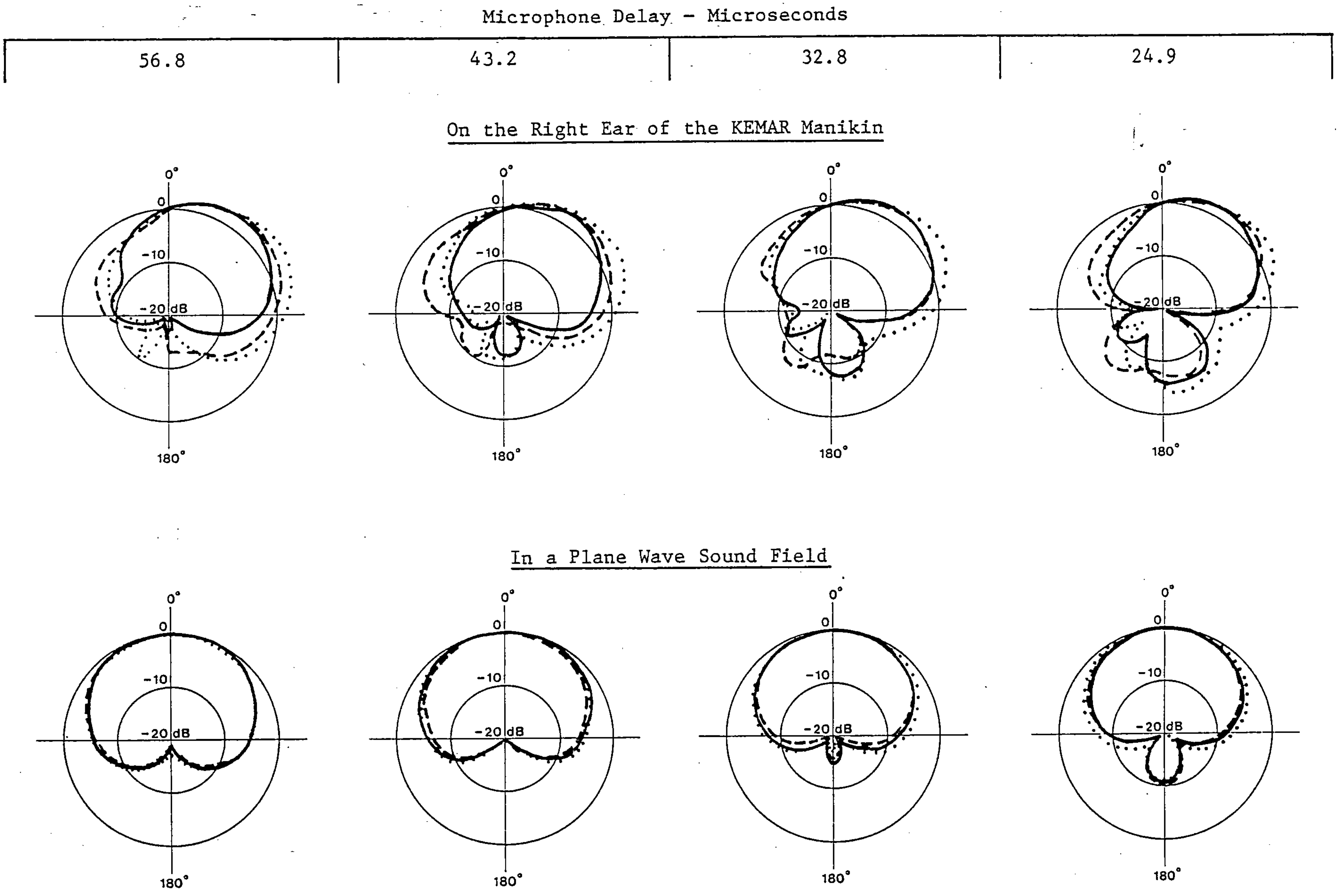
Microphone Cartridges Forming One Coordinate of the Matrix

FIG. 1



EXPERIMENTAL HEARING AID CONSTRUCTIONS

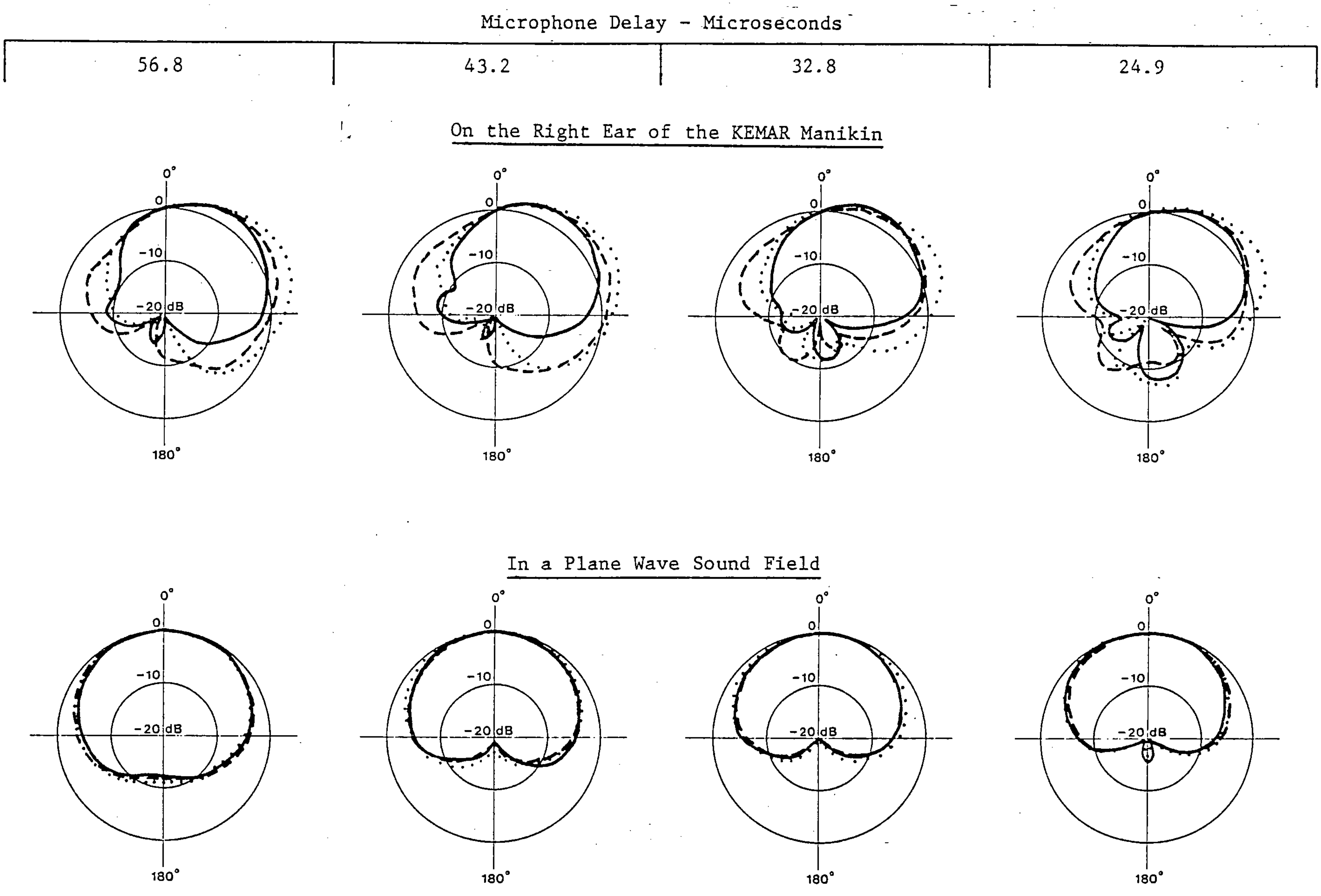
FIG. 2



POLAR RESPONSES

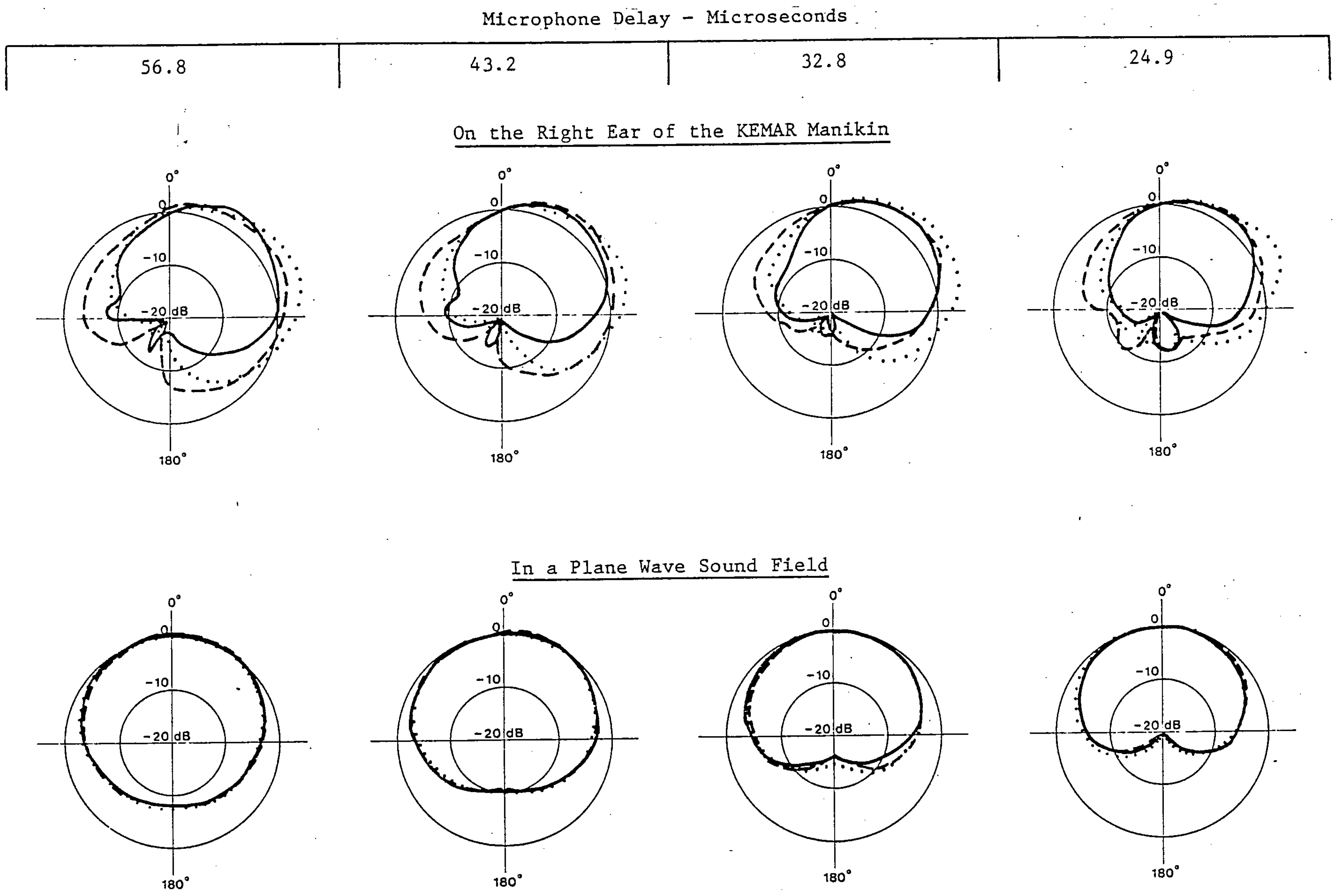
Behind-the-Ear Hearing Aid with 14.4 mm (.568") effective port spacing

FIG. 3



POLAR RESPONSES
Behind-the-Ear Hearing Aid with 11.0 mm (.432") effective port spacing

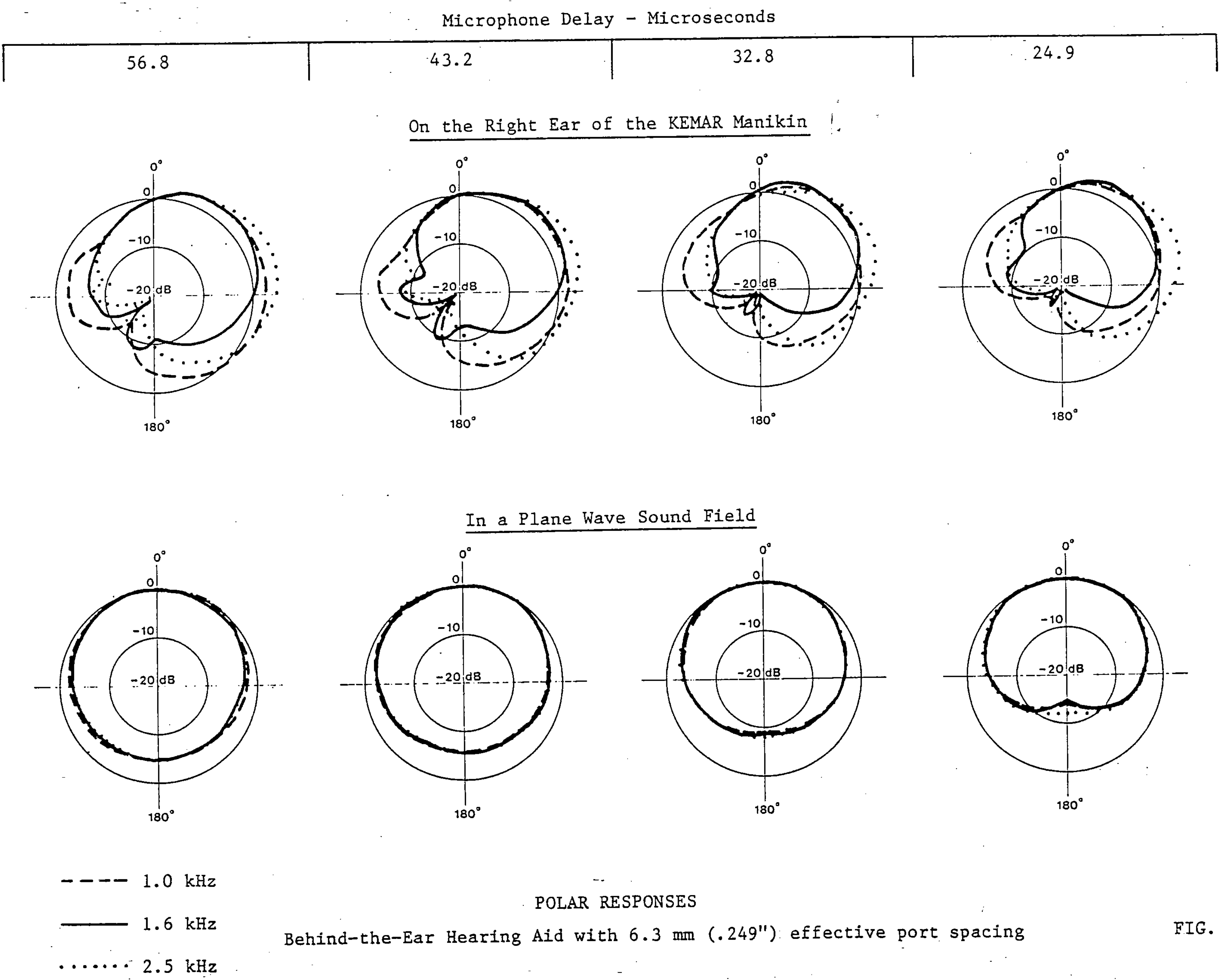
FIG. 4



POLAR RESPONSES

Behind-the-Ear Hearing Aid with 8.3 mm (.328") effective port spacing

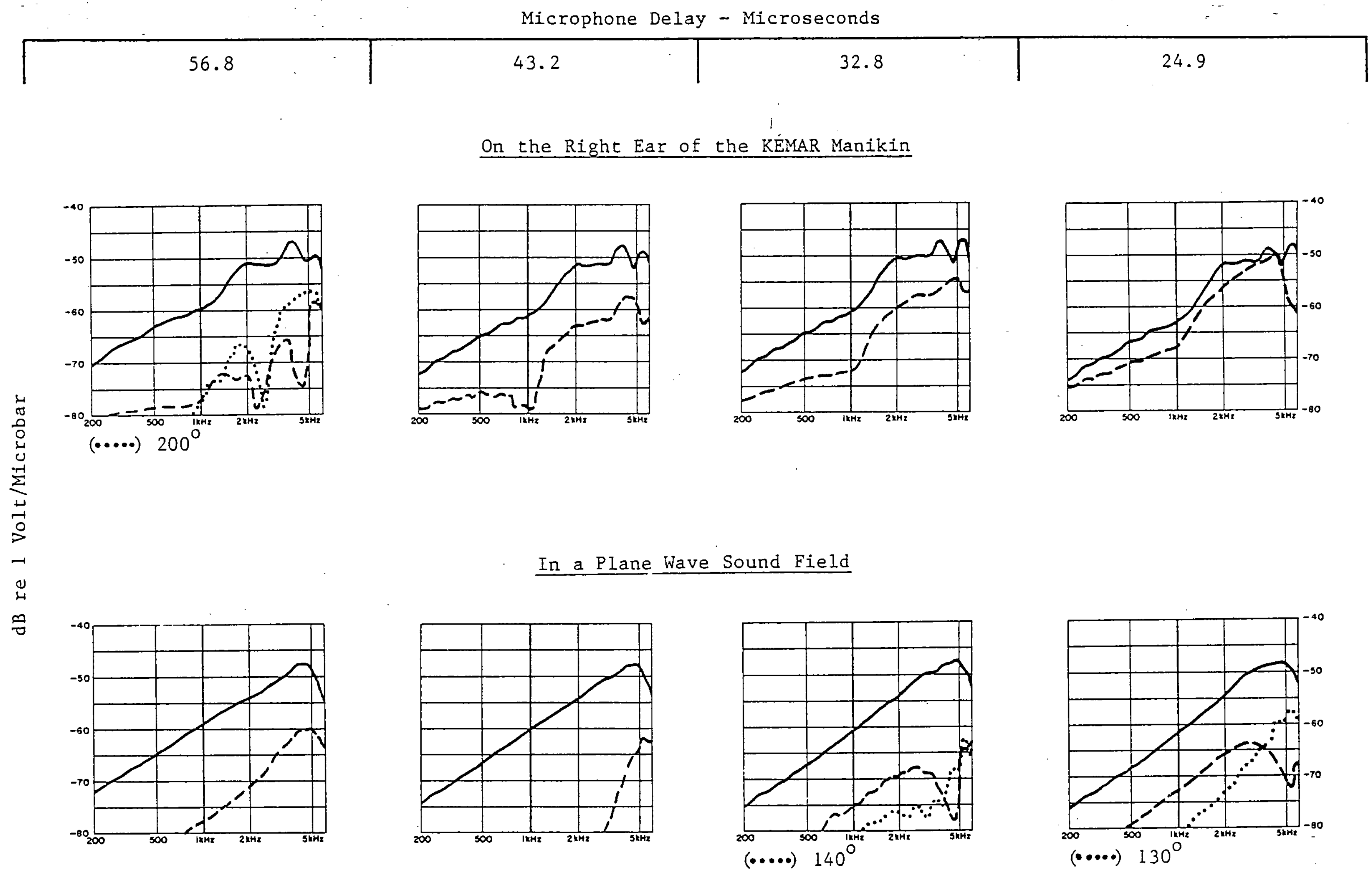
FIG. 5



POLAR RESPONSES

Behind-the-Ear Hearing Aid with 6.3 mm (.249") effective port spacing

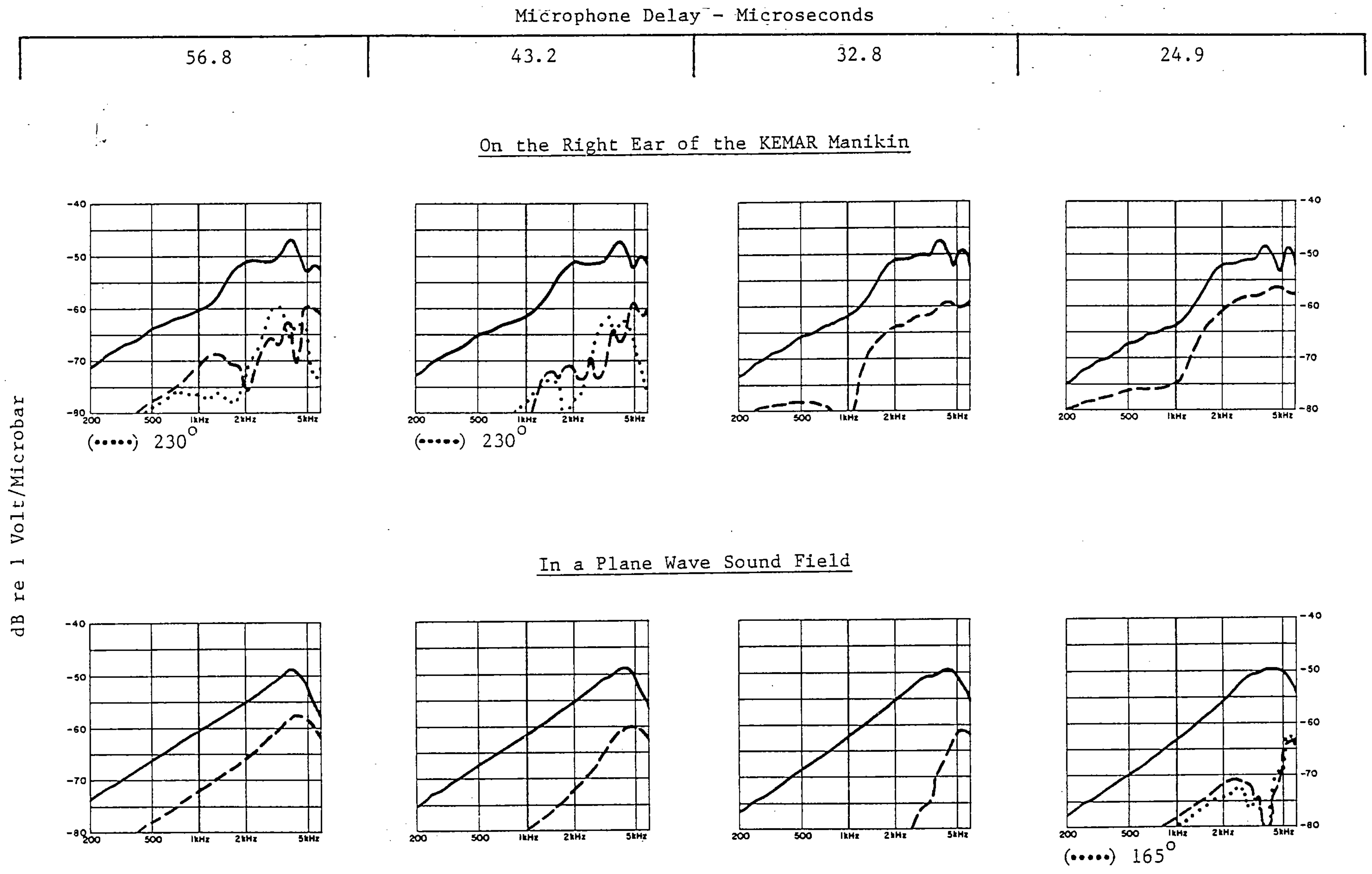
FIG. 6



FREQUENCY RESPONSES

Behind-the-Ear Hearing Aid with 14.4 mm (.568") effective port spacing

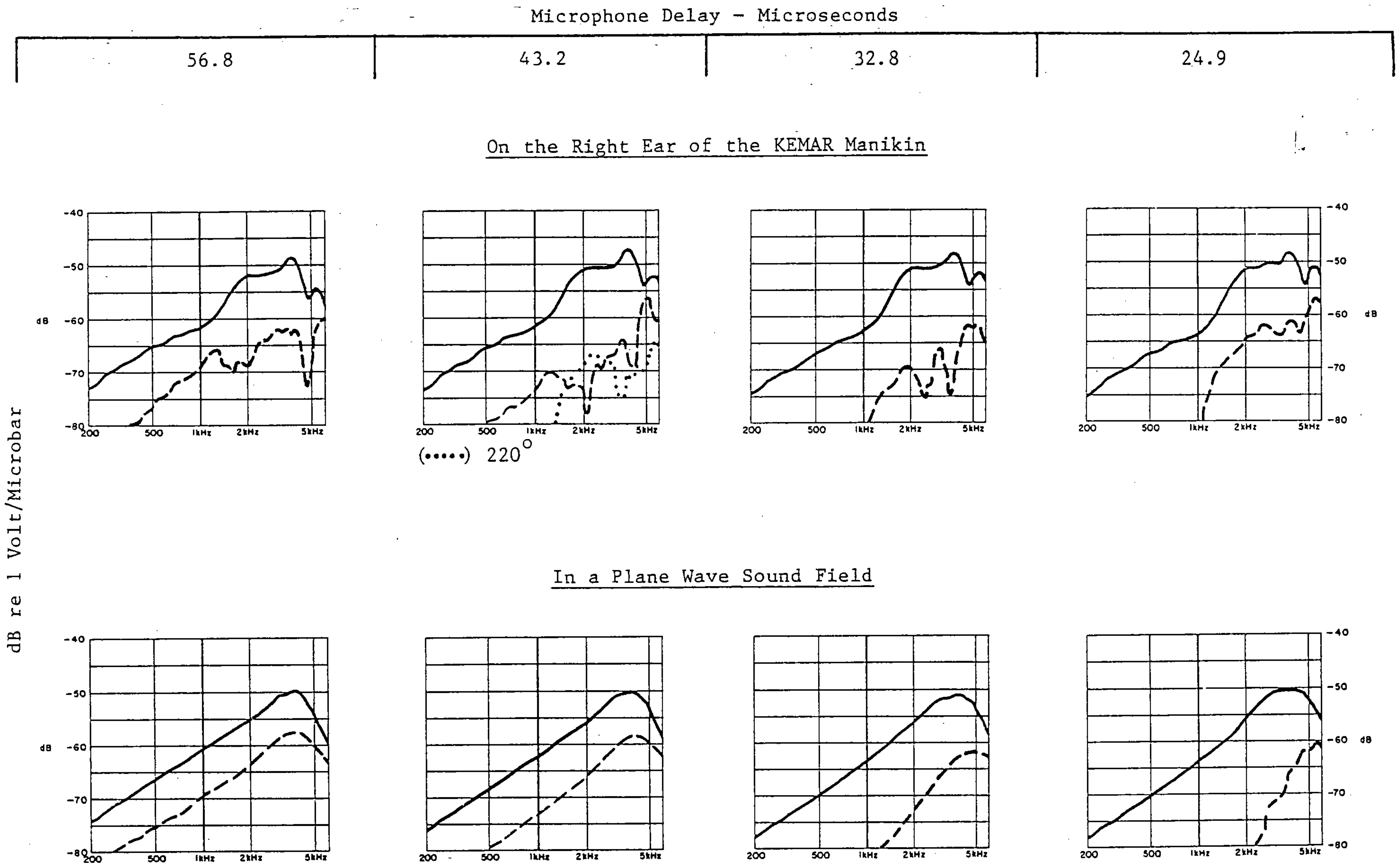
FIG. 7



FREQUENCY RESPONSES

Behind-the-Ear Hearing Aid with 11.0 mm (.432") effective port spacing

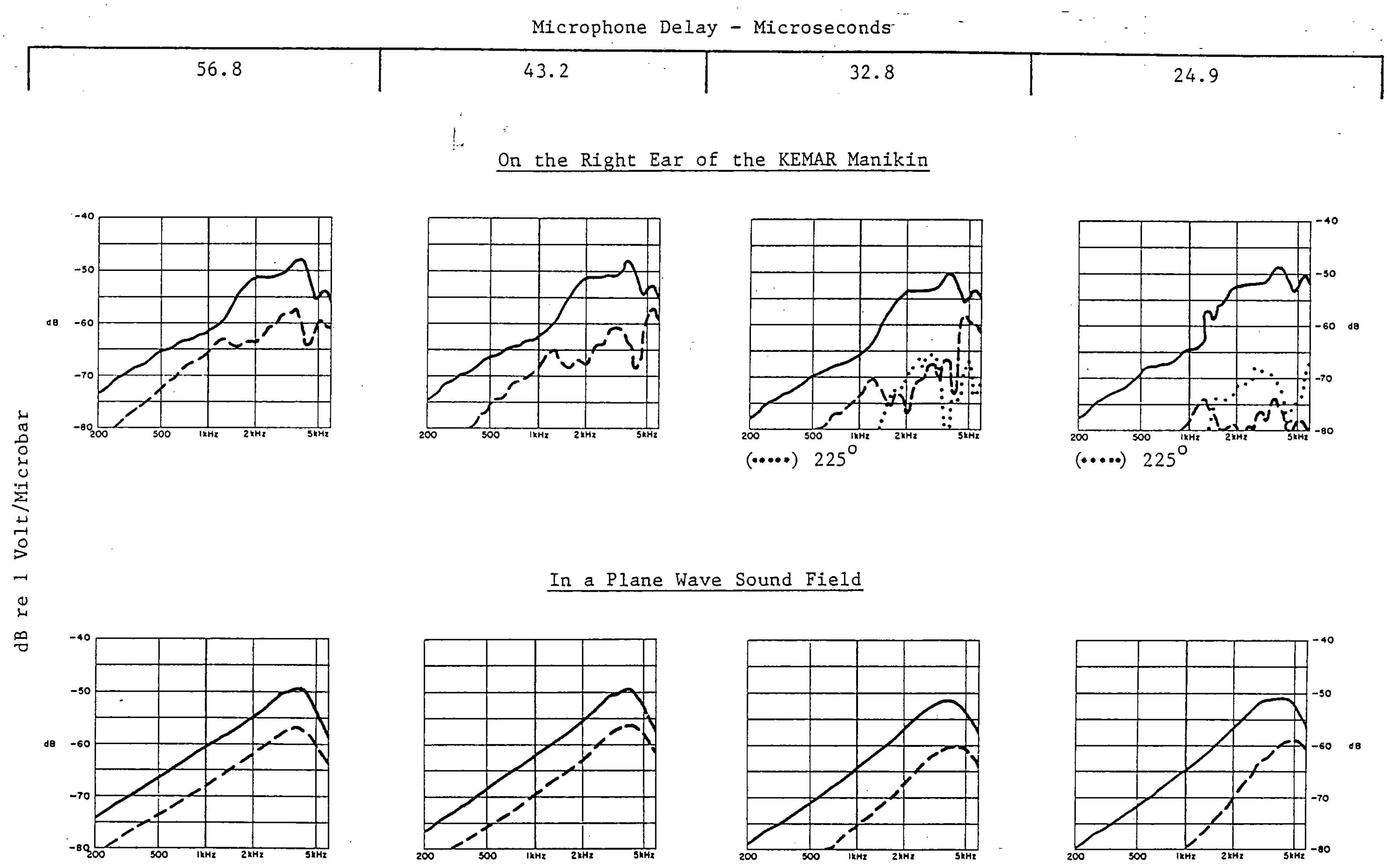
FIG. 8



FREQUĒNCY RESPONSES

Behind-the-Ear Hearing Aid with 8.3 mm (.328") effective port spacing

FIG. 9

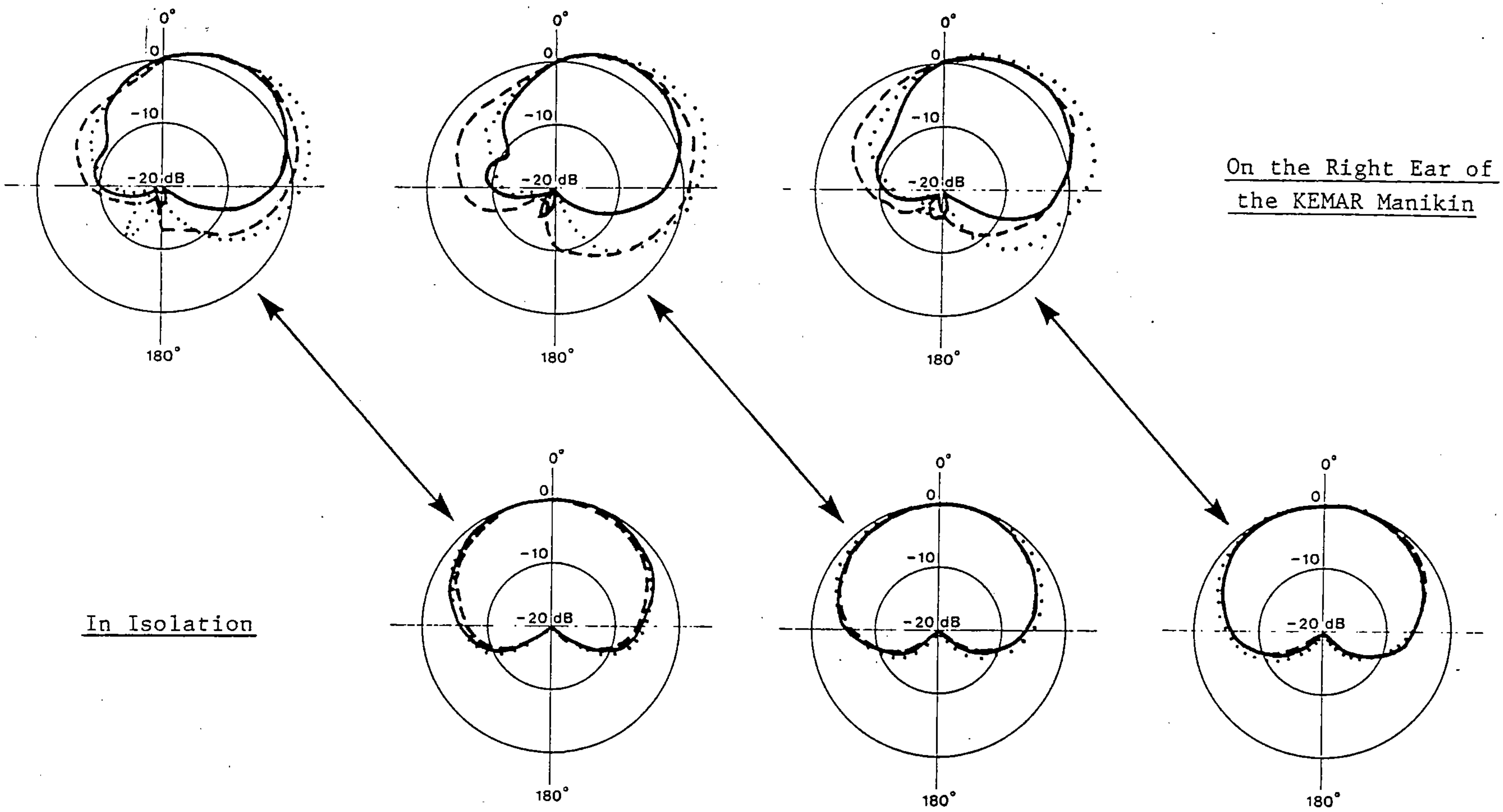


FREQUENCY RESPONSES

Behind-the-Ear Hearing Aid with 6.3 mm (.249") effective port spacing

FIG. 10

DELAY	56.8	43.2	32.8
SPACING	.568	.432	.328



DELAY	43.2	32.8	24.9
SPACING	.568	.432	.328

----- 1.0 kHz
——— 1.6 kHz
•••••••• 2.5 kHz

THE EFFECT OF A REDUCTION IN CARTRIDGE DELAY WHEN COMPARING POLAR PATTERNS MEASURED IN SITU AND IN ISOLATION

FIG. 11