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SOUND FIELDS AROUND THE HEAD/HANDSET SYSTEM AND THEIR EXPLOITATION FOR PRESSURE GRADIENT NOISE CANCELLATION.

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1.0 INTRODUCTION

Speech communication over the telecommunications network must often be attempted in conditions of high background noise. This is a particular problem when the telephone is used outside, for example payphones and mobile phones. Under these conditions even face-to-face conversations can become difficult.

This paper describes a novel noise cancelling handset which will make telephony possible in high levels of background noise. The user at the noisy location will benefit from reduced noise in the "telephony ear" via the sidetone path and the far end user from reduced background noise sent to line.

2.0 NOISE CANCELLING PERFORMANCE.

2.1 Objective Performance

The metric for the noise performance of a telephony handset is given in the CCITT recommendations and known as Delsm (or Δ_{SM}) [1].

$$\text{Delsm} = \frac{\text{Sensitivity to Noise (dBV/Pa)}}{\text{Sensitivity to Speech (dBV/Pa)}}$$

The measurement of Delsm is specified on an LRGP (Loudness Rating Guard-Ring Position) artificial head which does not simulate the obstacle effect of a human head and torso. This effect is important and an equivalent Delsm measurement was developed with the B&K Type 4128 HATS (Head And Torso Simulator). The results are in the form of a frequency spectrum, a more negative result representing greater discrimination of speech over background noise.

In order to simplify the presentation of performance results and to allow the rapid ranking of development models a single figure performance metric was required.

The Listener Sidetone Loudness Rating is defined but does not relate solely to the handset noise performance. Instead the Send Loudness Rating Weightings in BS6317 [2] are used to allow for the relative significance of different frequencies on the perceived loudness of the send path. In this way a SFDelsm (Single Figure Delsm) algorithm was constructed which gives an increasing positive value as discrimination of speech improves.

$$\text{SFDelsm} = 4/5 \sum_{n=1}^{14} \text{Del}_n * 10^{(-0.0175*W_{sn})}$$

Where:

	n	are the 14 standard test frequencies.
	Del_n	is the band pressure level centered on the n^{th} frequency.
	W_{sn}	is the SLR weighting for the n^{th} frequency.

A well designed but non-noise-cancelling handset such as that used on BT's Tribune telephone has a single figure performance metric of 3dB. Many poorly designed handsets are more sensitive to background noise than speech and give a negative SFDelsm.

3.2 Subjective Performance

The subjective significance of the noise cancelling performance offered by alternative designs must be evaluated in order to assess the perceived benefit to the telecommunications user. In practice this was achieved by two means:

- (i) Subjective performance assessment by experienced engineers.
- (ii) The use of a network performance modelling computer package developed at BTRL known as CATNAP [3]. The CATNAP program is able to predict the mean opinion score of a population of users for telephony connections.

A combination of these two methods serves to:

- (i) Indicate whether a solution is robust in terms of orientation on the head when in use by actual people for conversations in high background noise.
- (ii) Produce an estimate of the benefit to a population of users in terms of the improvement to the mean opinion score of a population of calls. This estimate can be used in conjunction with information about the background noise occurring at key operational sites to predict the increase in the percentage of time during which communication gives a mean opinion score above some minimum desirable value.

3.0 CONVENTIONAL NOISE CANCELLING HANDSET DESIGN

The conventional approach to noise cancelling handset design has relied on an open mouthpiece structure around a first order pressure gradient microphone. This type of microphone consists in its simplest form of a single diaphragm open on both sides.

With the diaphragm open on both sides the microphone output is proportional to the pressure difference across the diaphragm. The principal of operation is as follows. A small source radiating W Watts of acoustic power uniformly will produce an Energy Density, D, at a radius, r :

$$D = \frac{W}{4\pi r^2 c} \qquad (1)$$

Which is related to the sound pressure through the acoustic impedance :

$$D = \frac{p^2}{\rho_0 c^2} \qquad (2)$$

Combining equations (1) and (2) the average r.m.s. pressure is given by:

$$p^2 = \frac{W\rho_0 c^2}{4\pi r^2 c} \qquad \text{therefore,} \qquad p = \frac{1}{r}\sqrt{\frac{W\rho_0 c}{4\pi}} \qquad (3)$$

And hence $p \propto \frac{1}{r}$, while the sound pressure level, SPL α $p^2 \alpha \frac{1}{r^2}$

Thus for a doubling in radius $\Delta SPL = 10\log_{10}\left[\frac{(2r)^2}{(r)^2}\right] = 6dB$

Hence it can be seen that pressure differences will exist between points at different radii from the source. Further, since the sound pressure level is inversely proportional to the distance from the source, for a particular pair of points, the pressure difference due a to distant source will be small compared with that of an equivalent near source.

4.0 EXPERIMENTAL INVESTIGATION

An investigation was conducted into the limiting features of pressure gradient noise cancelling designs and the sound fields which exist around the handset-head-torso system.

The combination of pressure gradient noise cancellation which is effective at low to mid-range frequencies and noise-rejecting geometry which is effective at mid-range to high frequency potentially offers a broadband noise reduction solution.

4.1 Obstacle Effect or Sound Shadow

Due to the diffraction of sound around the handset and head an appropriately shaped handset geometry can "shade" the microphone from background noise. This method of noise rejection is only effective at mid-range to high frequencies where the wave-length is comparable with the dimensions of the obstacles.

Experiments were constructed to examine the sound pressures around the head-handset-torso using plane waves and reconstructed environmental noise in the BTRL large anechoic chamber.

Effective handset geometry has been developed [4] which provides useful noise-rejection. Figure 1 shows the noise cancelling performance of such a handset. The single figure performance metric for this result is 5dB.

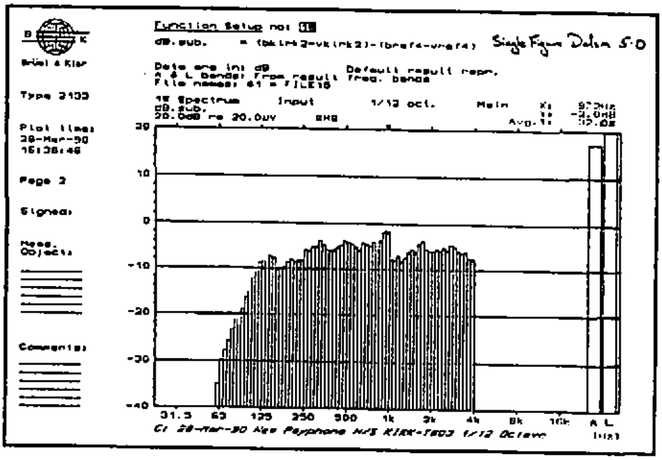

Figure 1

4.2 Separation of Pressure Gradient Sensing Locations

Theory indicates that the distance over which the pressure gradient is detected will determine the upper frequency limit of cancellation. The separation must be much smaller than the wavelength to be cancelled to ensure close phase matching of the pressures acting across the diaphragm, with the first limiting condition at $\lambda/4$.

If the case of a simple pressure gradient microphone in an open mouthpiece is considered then the separation of the pressure sensing locations is of the order of 7mm. In practice the upper frequency limit for cancellation is of the order of 3kHz and hence it can be seen that cancellation only occurs for a fraction of a wavelength, in this case:

$n = c/0.007.f$ therefore $n = 16$ i.e. $\lambda/16$.

This result indicates that the limiting frequency for cancellation is not dependent purely on the wavelength of the sound to be cancelled but also differences in the acoustic impedance to each side of the diaphragm.

4.3 Novel Pressure Gradient Cancellation.

It was reasoned that near-field effects are important for a handset solution, and that maximising the detection of pressure differences due to speech was potentially more useful than precise symmetry matching for distant sources. Locations on the face side of the handset were identified where sound arriving from a distant source produced a substantially equal sound pressure and where speech produced a large pressure difference. Figure 2 shows a diagrammatic cross-section of a handset illustrating these locations. The pressure sensing locations are separated by circa 75mm and discrimination of speech over background noise is possible up to an upper frequency limit of around 3kHz.

The sound arriving at the pressure sensing locations on the handset cannot be considered as plane waves. The sound field around the head results from direct and reflected energy making it practically impossible to identify simple wavelength effects to account for the properties discussed.

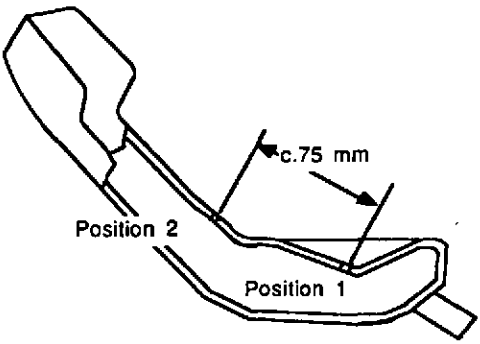

Figure 2

When the coherence between the two pressures was examined it was observed that a linear relationship exists between the detected signals at frequencies where cancellation occurs. The extent of cancellation decreases as the degree of linearity decreases.

Figures 3 and 4 show the coherence and phase relationship between two zero order microphones located at the sensing positions indicated in Figure 2.

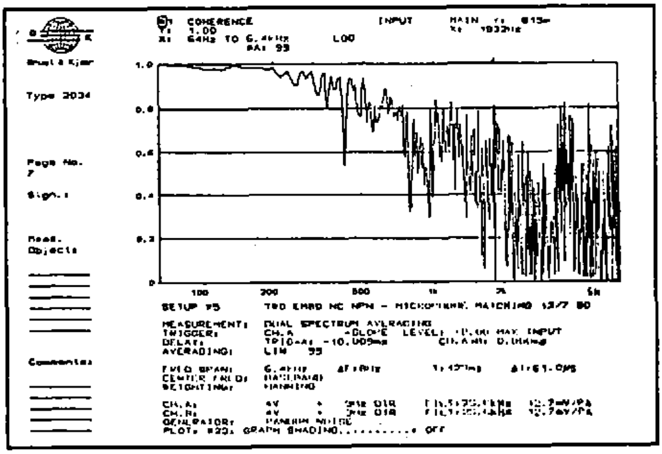

Figure 3

SOUND FIELDS AROUND THE HEAD/HANDSET SYSTEM FOR NOISE CANCELLING.

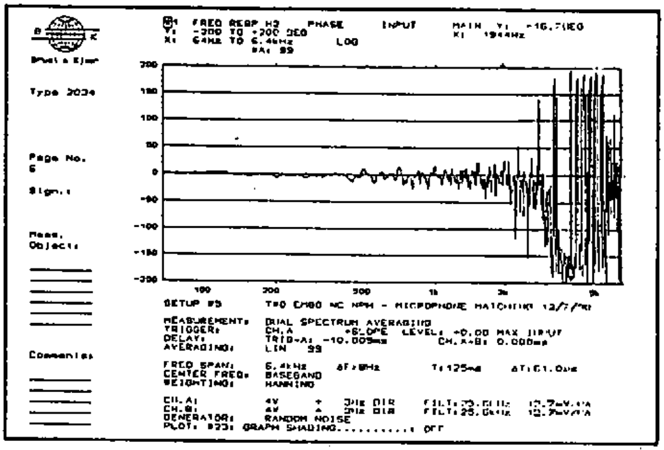

Figure 4

A measurement of the coherence [5] between the microphone signals was obtained using a B&K 2034 analyser where the coherence, γ^2 ,is given by:

$$\gamma^2(f) = \frac{|\overline{G_{AB}(f)}|^2}{\overline{G_{AA}(f)}.\overline{G_{BB}(f)}} = \frac{\text{Averaged Cross Spectrum}}{\text{Product Averaged Autospectra}}$$

A sampling time of 125ms was used to ensure that the measured coherence included the reflection effects of the interacting obstacles. Shorter sampling times would have registered reflected energy outside the sample frame as non-coherent noise and an artificially low measurement of coherence would result. Further, good signal to noise ratio was independently verified since the calculation method employed cannot distinguish between non-coherent noise and non-linearity.

The phase relationship between the two microphones remains within ±30° to about 2kHz. This is consistent with the upper frequency limit of cancellation.

A prototype noise cancelling handset was constructed by taking the difference between the signals detected by microphones located as in Figure 2. The performance of the prototype handset is shown in Figure 5. The single figure performance metric was calculated to be 12dB. The differential output may be obtained in practice with a simple op-amp circuit.

An alternative embodiment for a handset employing the novel gradient utilises a single first order pressure gradient microphone with the two sides of its diaphragm connected to the pressure sensing locations via a duct. This embodiment has been shown to work in the laboratory and would represent a low cost solution for a production handset.

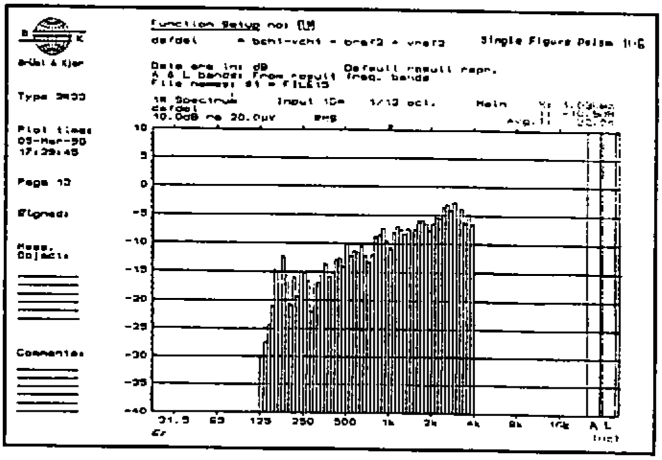

Figure 5

5.0 PERFORMANCE VERIFICATION WITH DIGITAL ADAPTIVE FILTER.

In principle when a pressure gradient is detected by two microphones these microphones should have precisely matched characteristics to maximise the cancellation possible.

The practical microphones used in the prototype will not exhibit perfect matching. The consequences of improving the microphone matching to near the ideal was investigated by including a digital adaptive filter [6] in series with one of the microphones.

The arrangement including the adaptive filter is shown in Figure 6.

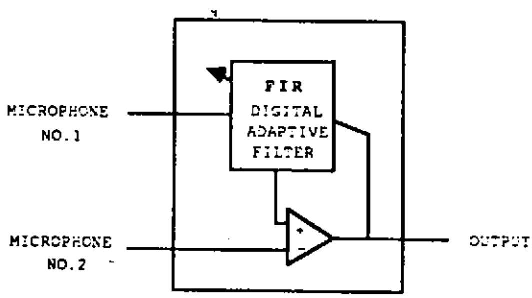

Figure 6

The adaptive filter was allowed to adapt to minimise the output in the presence of background noise. In this way the filter characteristic adapts to equalize detail differences between the two microphone responses. The filter response is then "frozen" (the filter no longer adapts) and the sensitivity to speech measured.

The Delsm performance can then be calculated producing a result indicative of that for perfectly matched microphones. The single figure performance metric was calculated to be 12.5dB demonstrating that microphone matching is not a limiting factor.

6.0 CONCLUSIONS

1. The noise reduction performance of the combined noise-rejecting geometry and pressure gradient cancellation is of great practical value.

2. The solution proposed uses low cost proprietary microphones and a simple analogue input circuit with little compromise from idealised performance.

3. The physical arrangement has a number of benefits for particular applications:
   - (i) Mechanically robust with no open grill areas.
   - (ii) The secondary pressure sensing location is on the face side of the handset and so is unlikely to be blocked by the users hand.
   - (iii) Moisture protection is simplified by the single hole secondary opening.
   - (iv) The components internal to the handset are compact.

4. If further electronic noise cancelling is employed then this task is simplified by the cleaner speech signal.

5. The acoustic noise cancelling method has advantages over certain digital signal processing techniques in that it will still operate when:
   - (i) The background noise level is greater than or equal to the speech level.
   - (ii) The background noise is speech.

6. The use of widely spaced pressure sensing location on the face side of the handset is thought to be novel and a patent application has been registered, British Patent Application No.9019448.1.

7. REFERENCES

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[6] South C R : An adaptive filter in LSI, British Telecom Technology Journal, Vol.3, No.1, January 1985.