ISSN 0280-6819

TECHNICAL AUDIOLOGY

Report TA No. 110
January 1984

IMPROVEMENT OF INDUCTION LOOP FIELD CHARACTERISTICS USING MULTI-LOOP SYSTEMS WITH UNCORRELATED CURRENTS

Åke Olofsson

Karolinska Institutet
Dept. of Technical Audiology
KTH
S-100 44 Stockholm
Sweden
Tel: +46-8-11 66 60

Report TA110
January 1984

IMPROVEMENT OF INDUCTION LOOP FIELD CHARACTERISTICS USING MULTI-LOOP SYSTEMS WITH UNCORRELATED CURRENTS

Ake Olofsson

ISSN 0280-6819
Report TA110
January 1984

Karolinska Institutet
Dept. of Technical Audiology
KTH
S-100 44 Stockholm
Sweden
Tel: +46-8-11 66 60

IMPROVEMENT OF INDUCTION LOOP FIELD CHARACTERISTICS USING MULTI-LOOP SYSTEMS WITH UNCORRELATED CURRENTS

Åke Olofsson

ABSTRACT

This report deals with the advantages and disadvantages of induction loop systems consisting of multiple-loops carrying uncorrelated currents as compared to single-loop systems. Multiple-loop systems are shown to give better performance regarding signal attenuation outside loop area thus reducing cross-talk between adjacent rooms. They also give more uniform magnetic field strength in a room at a given listening height, but give greater variation in field strength with changes in listening height.

This work was supported by the National Swedish Board for Technical Development.

INTRODUCTION

Hearing aid users often have great problems to use their hearing aids for listening in public places like auditoria, theatres and lecture rooms. The reasons are, among other things, the high level of background noise and the deteriorated ability of localization due to the hearing aid. As a hearing impaired person normally requires higher signal to noise ratio than a normal hearing person does, listening in those places is very tiring for the hearing aid user. One way to increase the signal to noise ratio is to use the telephone pick-up coil of the hearing aid instead of the microphone and transmit the program signal via an induction loop rather than acoustically. Such systems are extensively used in Sweden, both in public places as those mentioned above and in homes.
In recent years communication systems using infrared light have become rather common. Very few hearing aids, however, have possibility to receive infrared signals. On the contrary, most aids are equipped with a telephone pick-up coil and therefore communication systems utilizing induction loops will be more common than infrared communication systems in the foreseeable future.

If the induction loop system is correctly designed and the signal level properly adjusted, the system will work very well provided there are no disturbing magnetic sources in the neighbourhood. Examples of such disturbing sources are the AC mains and cross-talk from induction loops in adjacent rooms. Another problem might arise when the hearing aid user does not sit as upright as the orientation of the pick-up coil presupposes and the magnetic field component along the axis of the coil becomes too weak.
Both these problems can be solved by introducing, in each room, two different systems of loops with their currents 90 degrees out of phase. By arranging the induction loops in well calculated patterns the resulting maxima of one loop system can be made to compensate the minima of the other loop system making the total magnetic field more uniform across the listening area. This is true not only for the vertical magnetic field but also for the horisontal field. The orientation of the pick-up coil is therefore not as critical as with a one-loop system. This is a great advantage, especially in school situations. At the same time the field outside the listening area decreases rapidly. The theory will be described in the next section.

MULTILOOP SYSTEMS

When a conventional induction loop system is set up the installation is rather simple. Just one loop of wire is fixed to the wall or to the floor to surround the listening area. Figure 1 shows an example, where one turn of wire is placed around a room with the area 10 by 20 metres. Especially when the listening height is small compared to the loop dimensions, the level of the magnetic field in the centre of the loop is low compared to the level close to the wire. (Throughout this paper the listening height refers to the distance between the pick-up coil and the plane of the loop).

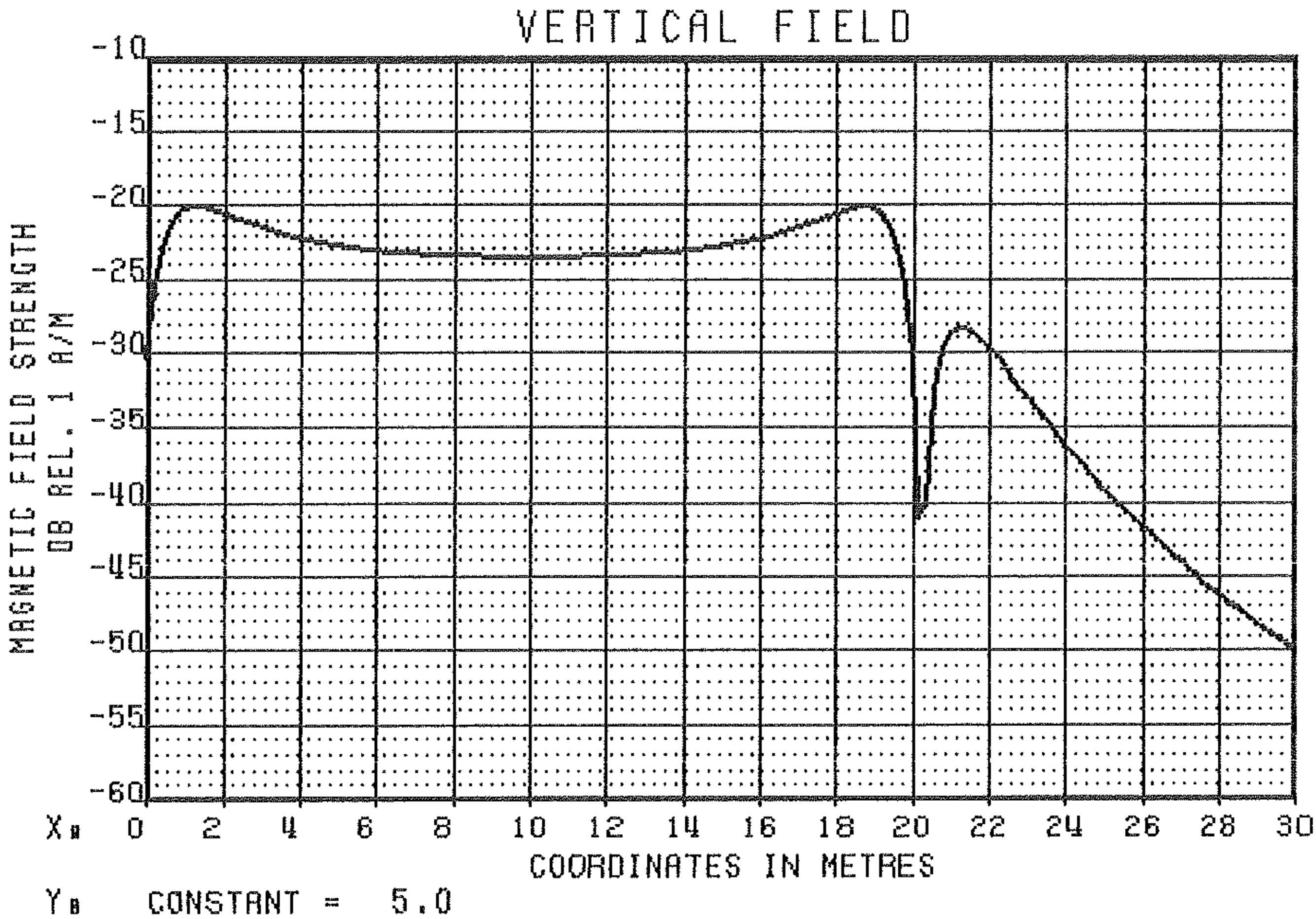


Figure 1. Vertical magnetic field strength along the long median line of a room surrounded by a loop with a current of 1 Ampere. Room dimensions 10 by 20 metres. Listening height 1.20 metres.

An often used way to increase the level in the middle of the room is to arrange the wire in many small loops of the same shape and size. The resulting magnetic field strength in such a case is shown in figure 2. In this case there are seven loops each covering an area of 10 by 2 metres and with a spacing between the loops of 1 metre. It can be seen that there are several peaks of equal height.

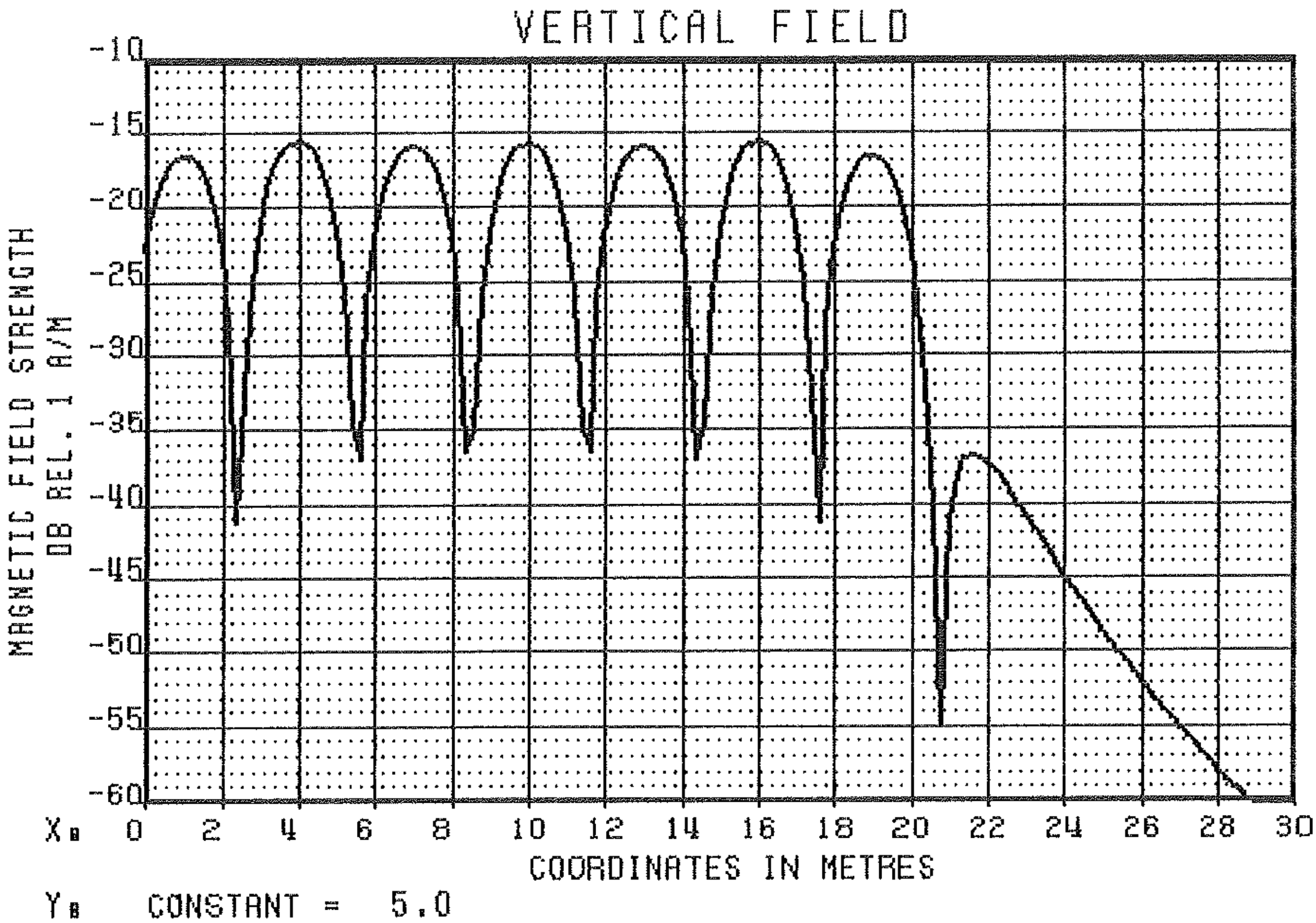


Figure 2. Vertical magnetic field strength along the long median line of a room with one set of sub-loops with currents of 1 Ampere. Room dimensions 10 by 20 metres. Listening height 1.20 metres.

The vertical magnetic field in figure 2 has zeros above the wires because the field is entirely horisontal there. It is however possible to arrange another set of loops of equal shape and size, but displaced half a loop width, in such a way that the peaks of the field of the second set of loops cover the zeros of the first one. If the loops carry the same current, this will of course lead to a new set of zeros, but if the currents are made uncorrelated, the field will be uniform with no zeros within the loop area (Bosman et al., 1965; Umbach, 1975), as can be seen in figure 3. The field outside the loop area is decreasing more rapidly in this case as compared to the case of a single loop.

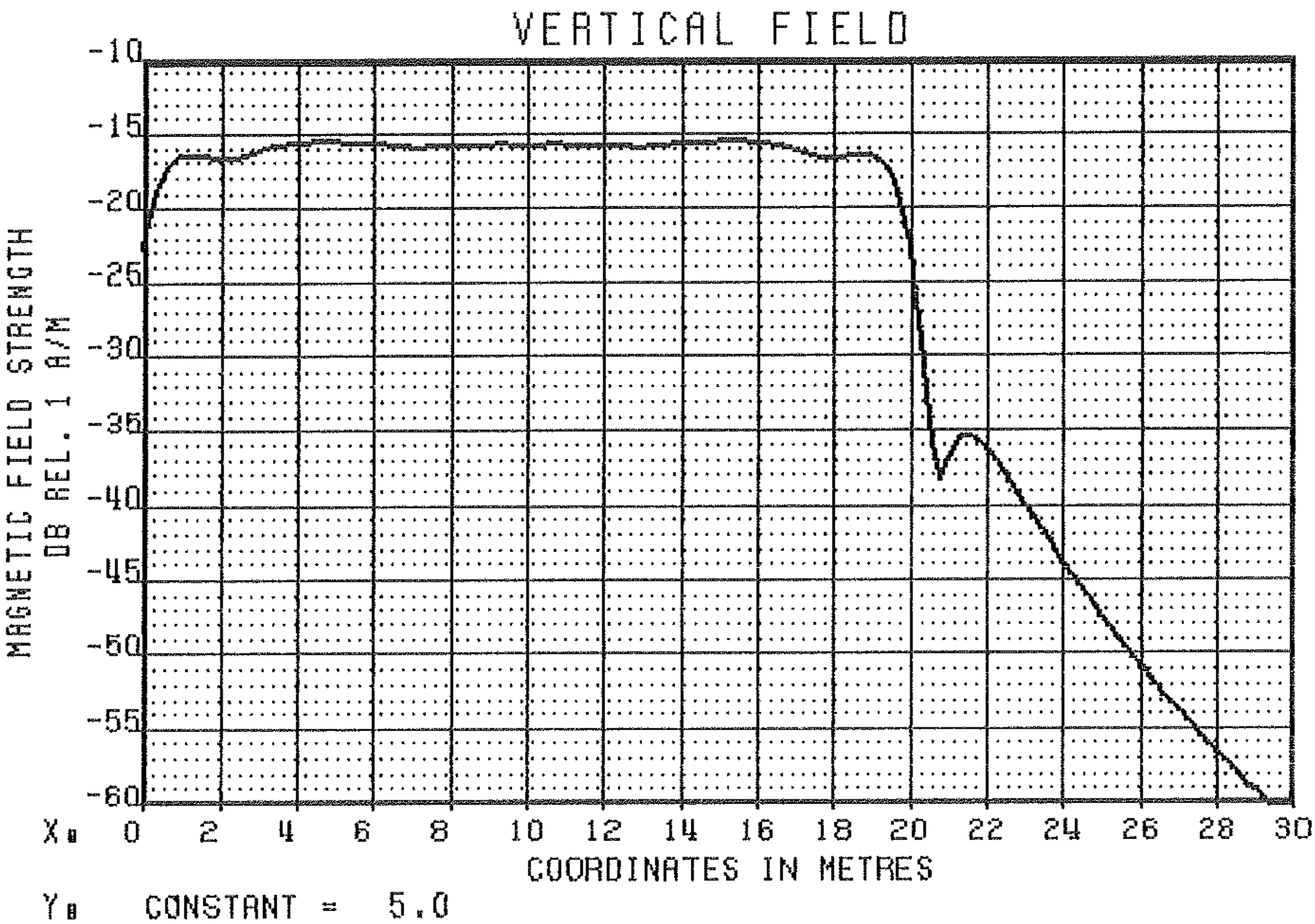


Figure 3. Vertical magnetic field strength along the long median line of a room with two sets of sub-loops with uncorrelated currents of 1 Ampere. Room dimensions 10 by 20 metres. Listening height 1.20 metres.

So far all curves were calculated along the long median line of the room. In figure 4 the magnetic fields from the one-loop system and the multi-loop system are shown, calculated along a parallel line 10 metres outside the room.

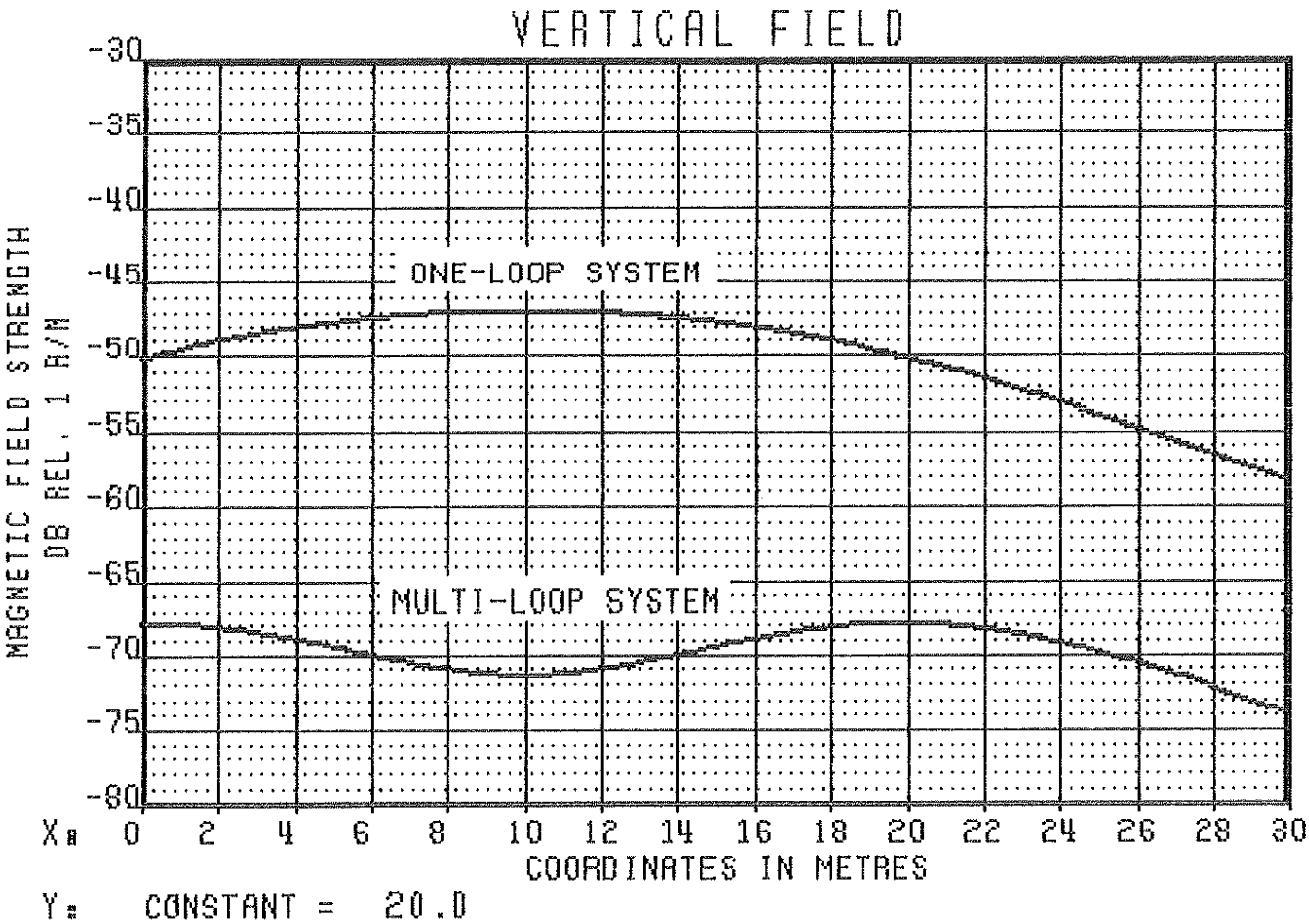


Figure 4. Comparison between the vertical magnetic field strengths of a one-loop system and a multi-loop system along a line 10 metres outside a room parallel to the long median line. Room dimensions 10 by 20 metres. Loop currents 1 Ampere. Listening height 1.20 metres.

The difference in attenuation is even more pronounced than along the median line. The difference is in fact 8 dB more than can be seen from figure 4 as the multi-loop system gives 8 dB higher level than the one-loop system inside the listening area. The cross-talk is thus reduced at least 20 dB at distances 10 metres outside the room.

As mentioned above, it is possible to arrange the two sets of loops in such a way, that when one set of loops gives a high vertical magnetic field component, the other gives a high horisontal field component and vice versa. It is thus possible to obtain not only a uniform vertical field, but also a uniform horisontal field, as is shown in figure 5.

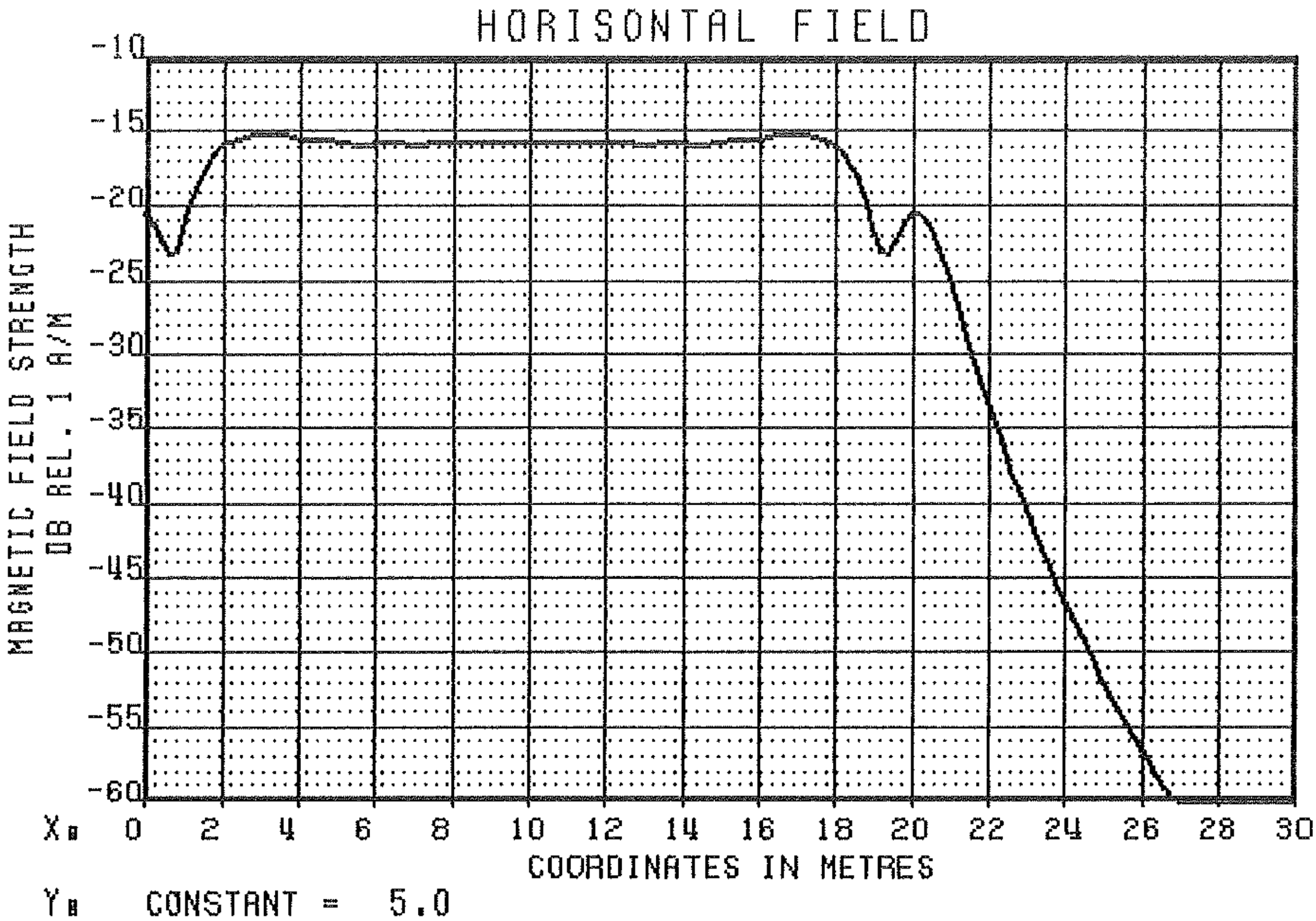


Figure 5. Horisontal magnetic field strength along the long median line of a room with two sets of sub-loops with uncorrelated currents of 1 Ampere. Room dimensions 10 by 20 metres. Listening height 1.20 metres.

The loop system can therefore be designed to give vertical and horisontal fields of equal strength over most of the listening area. As the two components are uncorrelated, i.e. 90 degrees out of phase, the resulting magnetic field vector is rotating in a vertical plane. As is shown in Appendix A a pick-up coil in this plane will pick up the same signal independent of how it is oriented in the plane.

One thing to bear in mind when designing multi-loop systems is the increased variation of the field strength with varying listening height, when the size of the loop is decreased. The maximum allowed change in magnetic field strength between the lowest and the highest listening heights will therefore determine the smallest permissible loop size. Table 1 gives the difference in field strengths between 0.75

metres and 1.5 metres listening heights for different dimensions of a single sub-loop. Inductance values are also shown in the table.

Level differences (dB)

Side 1 (metres) \ Side 2 (metres)	2	6	9	12
2	8	6	6	6
3	7	4	4	4
4	6	3	3	3
5	6	2	2	2

Inductances (μH)

Side 1 (metres) \ Side 2 (metres)	2	6	9	12
2	12	26	36	46
3	16	30	41	51
4	19	34	45	56
5	23	38	49	61

Table 1. Differences between the vertical magnetic field strengths at listening heights of 0.75 and 1.5 metres in the middle of rectangular loops of different sizes.

Inductances in μH of rectangular one-turn loops of different sizes with wire area 1 mm^2.

EXAMPLES

Two multi-loop induction systems were installed, and simulation results were tested against measured values. One of the installations was made in an assembly hall. Loop configuration, calculated magnetic fields and measured field values are plotted in appendix B. Appendix C shows the corresponding plots for the other installation, made in a small lecture room. In the appendices calculated fields for single-loop installations are also shown. As expected, the fields outside the listening area are more attenuated in the multi-loop case than in the one-loop case. The magnetic field strength on the next floor (listening height 3.80 metres) has decreased 19 dB relative to the level at 1.20 metres as compared to 4 dB in the one-loop case. In the lecture room measured and calculated values correspond very well for the vertical field but the measured horisontal field is 3 dB lower than calculated. In the assembly room the discrepancy is even greater. The measured vertical field is 5 dB and the horisontal field 4 dB lower than the calculated fields. The reason for this is the reinforcement bars in the concrete of the buildings. This is confirmed by the fact that the difference between calculated and measured fields in the assembly room have increased to 10 dB for a listening height of 3.80 metres, i.e. when the field has passed the ceiling to the next floor.

In the examples above it has been shown that multi-loop systems with uncorrelated currents can be used to reduce cross-talk between induction loop installations.

There are other applications where induction loops with uncorrelated currents can be of great value. For example in a large room surrounded by a single loop there might be some areas where the magnetic field strength is low. It is then possible to arrange small loops around these areas and feed the main loop and these small loops with uncorrelated currents in order to increase the field locally without disturbing the magnetic field in other points of the room.

DISCUSSION

A phase-splitting network that gives two output signals with a phase difference of 90 degrees over the frequency range of interest, are normally used to obtain uncorrelated currents out of one original signal. Another way is to use the original signal and a time delayed version of it. This is obviously not the same as a phase difference of 90 degrees. However, the autocorrelation of speech signals is rather low when the time lag approaches 10 milliseconds, and the currents will be almost uncorrelated. However, for some orientations of the pick-up coil the signal will be comb-filtered, with zeros depending upon the choosen time delay. This filtering will not be of any practical importance if the zeros and peaks of the filter are close enough in frequency to give the filtered signal approximately the same energy as the original signal in most critical bands. If on the other hand the zeros of the comb filter are too close in frequency this will correspond to a time delay that is too long, giving an impression of a direct signal and an echo signal. A suitable choice of the time delay should thus be between 10 and 20 ms, giving zeros every 100 to 50 Hz.

In appendix A it was shown that it is possible to get a magnetic field vector that rotates in a plane by having two uncorrelated orthogonal field components in this plane.
As mentioned in the appendix, a pick-up coil in the plane will pick up the same signal (except for phase lag) independent of its orientation.

Sometimes it would be desirable to be independent of the orientation of the pick-up coil not only in one plane but in all three dimensions. When a phase difference of 90 degrees between two signals is used to achieve uncorrelated currents, obviously only two currents and thereby two magnetic field components can be made uncorrelated. But if time delays between signals, as described above, are used instead, there is no problem to obtain three or more uncorrelated currents. It is therefore feasible to make magnetic fields which are rotating in all three dimensions, and thereby make the signal picked up by the coil totally independent of its orientation.

With multi-loop induction systems as described above, it is also possible to get an arbitrarily good attenuation of cross-talk to listening positions outside the desired listening area. This is obtained by increasing the number of sub-loops and making them narrower. Thereby the attenuation in the vertical direction will also be considerably increased. In the loop installation shown in appendix B, the attenuation to the next floor above has increased with 26 dB as compared to the one-loop case. However, this also means that the field is varying more over actual listening heights. The design of a multi-loop system therefore has to be a compromise between desirable attenuation outside the listening area and desirable homogeneity of the field within this area.

ACKNOWLEDGEMENT

I would like to express my gratitude to my colleagues for many valuable discussions upon the subject of induction loop systems and for their encouragement and criticism during the preparation of this report.

REFERENCES

Bosman, D. & Joosten, L.J.M. (1965). A New Approach to a Space-Confined Magnetic Loop Induction System. IEEE Trans on Audio AU-13, No. 3, 47-51.

Kringlebotn, M. & Sörsdal, S. (1981). Guidelines for the Dimensioning of Induction Loop Systems. Scand Audiol 10, 225-233.

Lindblad, A.C. (1969). Some Viewpoints on the Magnetic Field for the Test of Induction Pick-up Coils in Hearing Aids. Technical Audiology Reports, Karolinska Institute, Stockholm, No. 61.

Umbach, F.W. (1975). Loop-Induced Magnetic Fields with Negligible Side-Lobes. Acustica 33, 55-58.

APPENDIX A:

Given a pick-up coil with its axis in the x-y-plane at an angle θ to the x-axis, then

$$H(\theta)=H_x \cos\theta + H_y \sin\theta$$

where H_x and H_y are the magnetic field components in the x- and the y-directions respectively and $H(\theta)$ is the resulting field in the coil.

If further

$$E\{H_x^2\}=E\{H_y^2\}=\sigma_1^2 \text{ and } E\{H_xH_y\}=\sigma_1^2\rho_{xy}$$

where E{ } denotes the expected value and ρ_{xy} is the correlation between H_x and H_y, then

$$\sigma_2^2=E\{H^2(\theta)\}=\cos^2\theta\ E\{H_x^2\}+\sin^2\theta\ E\{H_y^2\} + 2\ E\{H_xH_y\} \cos\theta \sin\theta$$

This gives

$$\sigma_2^2=\sigma_1^2\ (1+\rho_{xy} \sin 2\theta)$$

If $\rho_{xy}=0$, then $\sigma_2^2=\sigma_1^2$ independent of θ.

If for instance the x- and y- components of the magnetic field are

$$H_x=H_0 \cos(\omega t+\varphi) \text{ and } H_y=H_0 \sin(\omega t+\varphi)$$

where H_0 is a constant and φ is a random variable uniformly distributed over the interval 0 to 2π, then $\rho_{xy}=0$.

This gives

$$H(\theta)=H_0 \{\cos(\omega t+\varphi)\cos\theta+\sin(\omega t+\varphi)\sin\theta\}= =H_0 \cos(\omega t+\varphi-\theta)$$

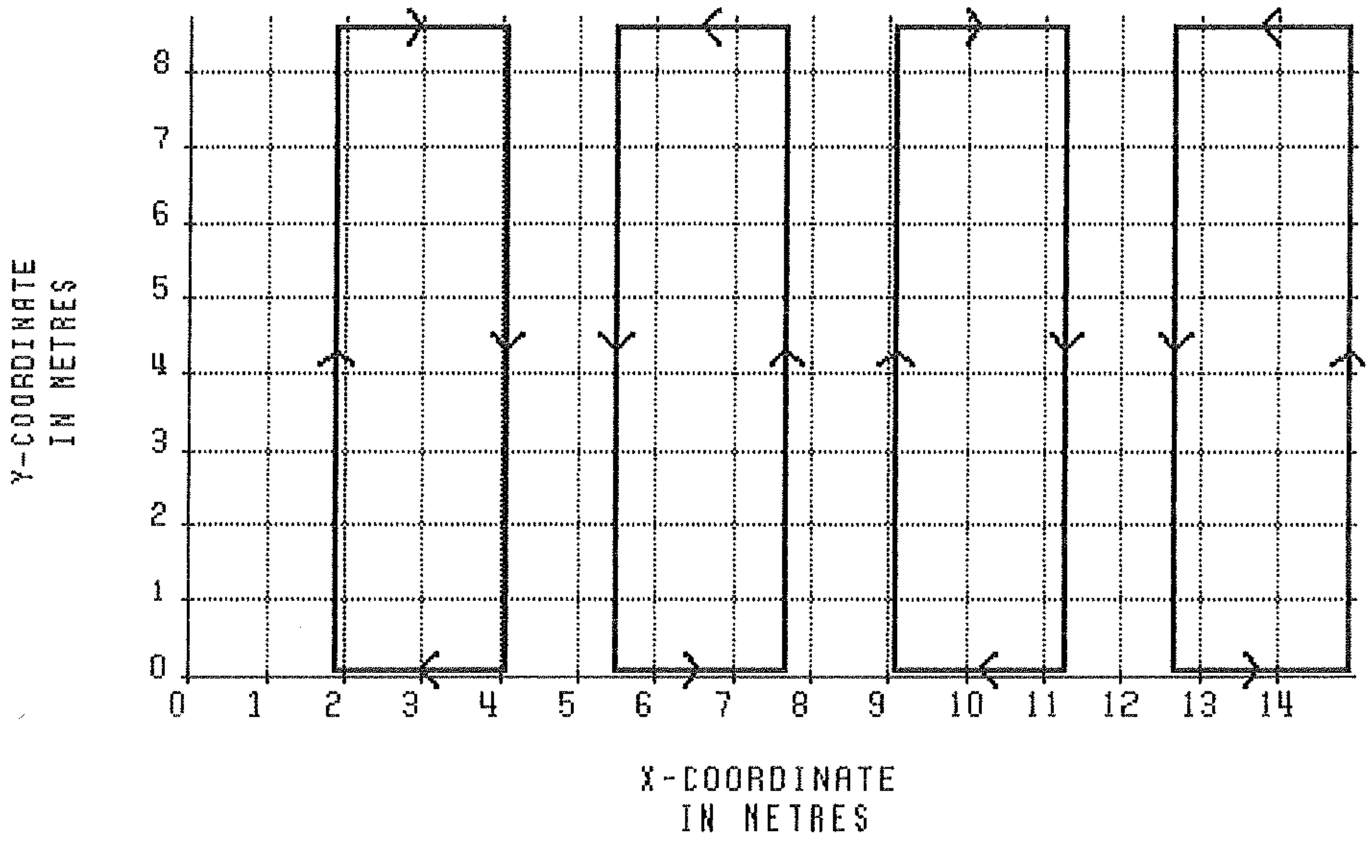
e.g. the level is independent of θ. This means that the magnetic field vector is rotating in the x-y-plane with an angular frequency of ω radians per second.

APPENDIX B:

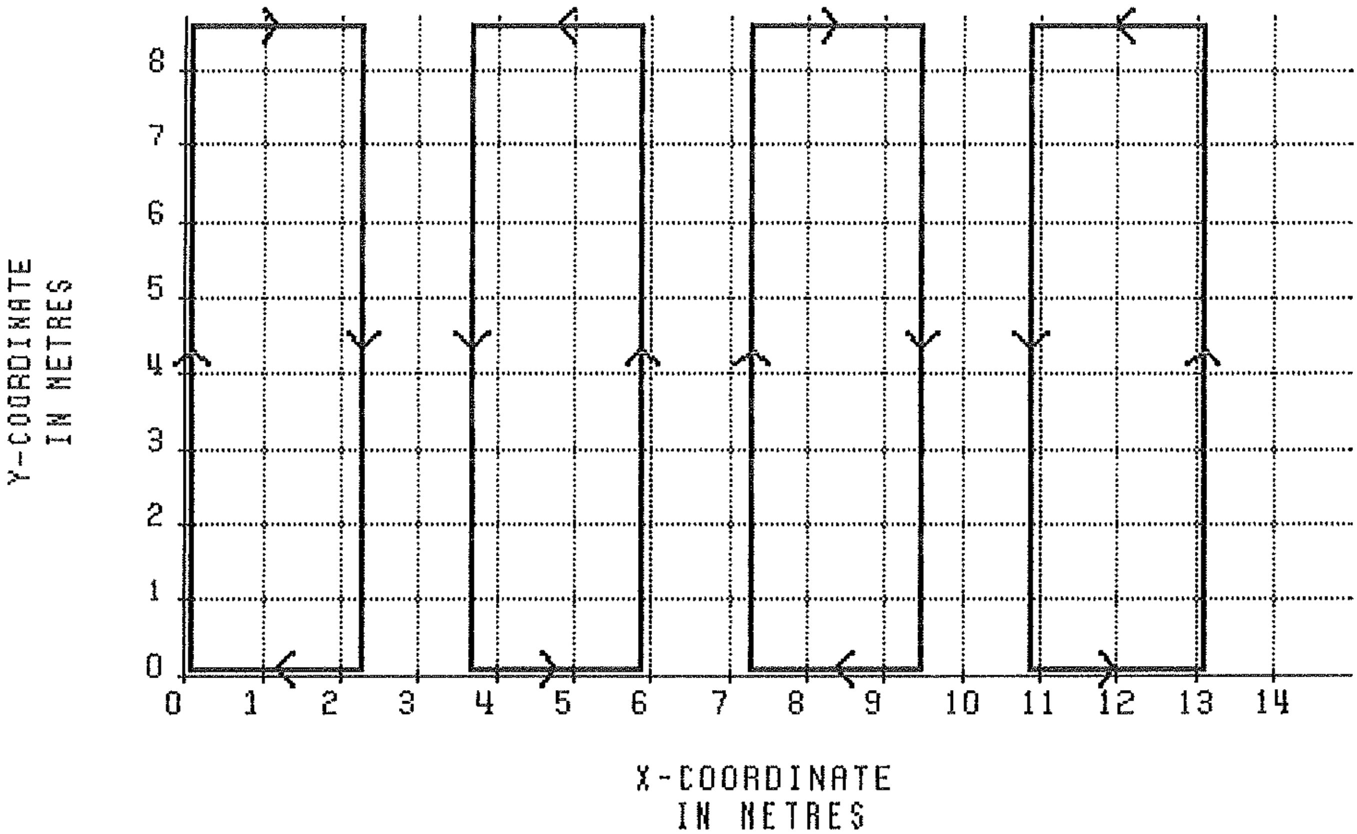
LOOP INSTALLATION IN AN ASSEMBLY HALL WITH DIMENSIONS 8.90 BY 16.20 METRES. LISTENING AREA 8.70 BY 15.00 METRES.

Loop configurations

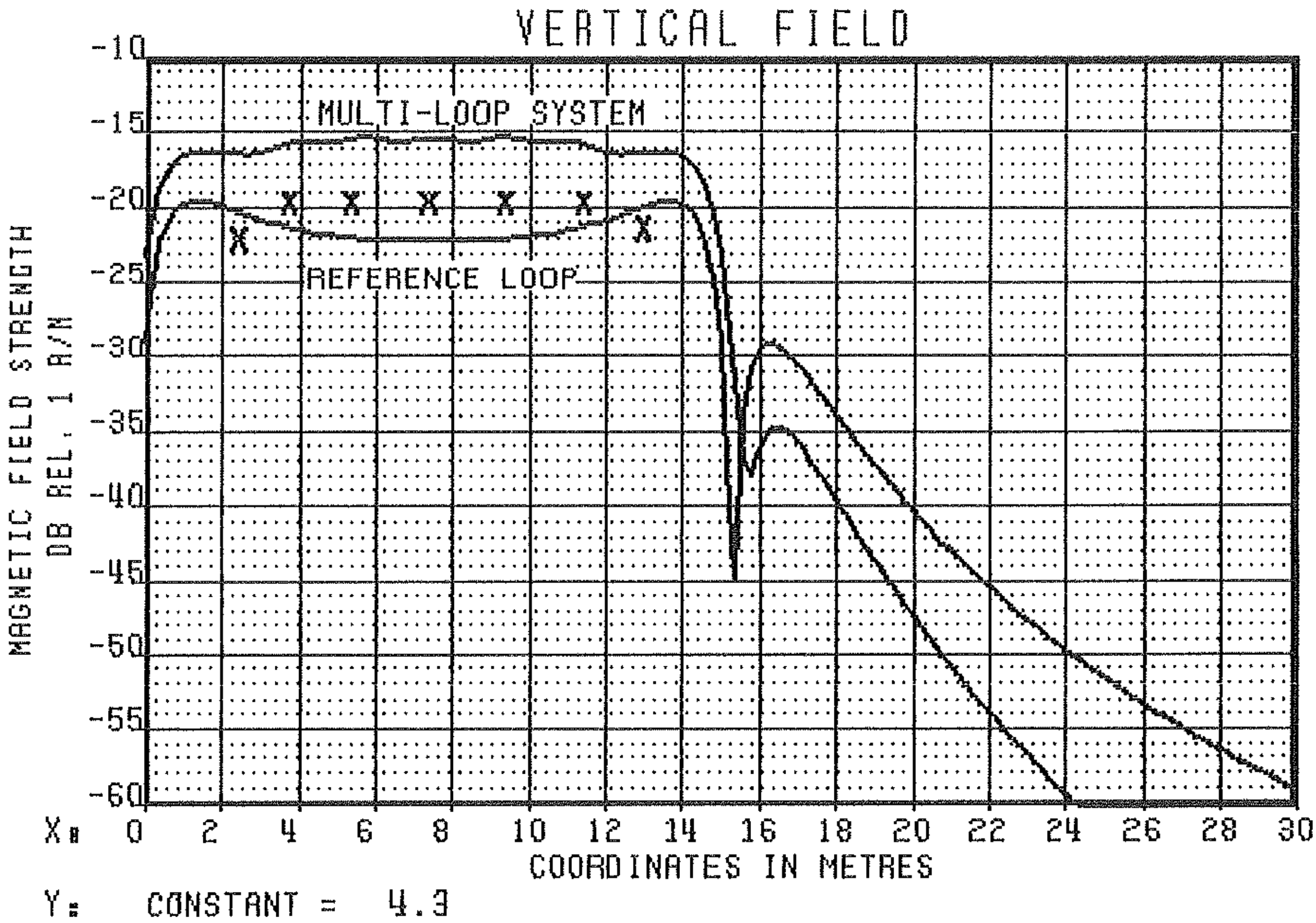
Loop 1: 4 sub-loops (calculated inductance 37 µH/ sub-loop, measured inductance 125 µH for the sub-loops connected in series).

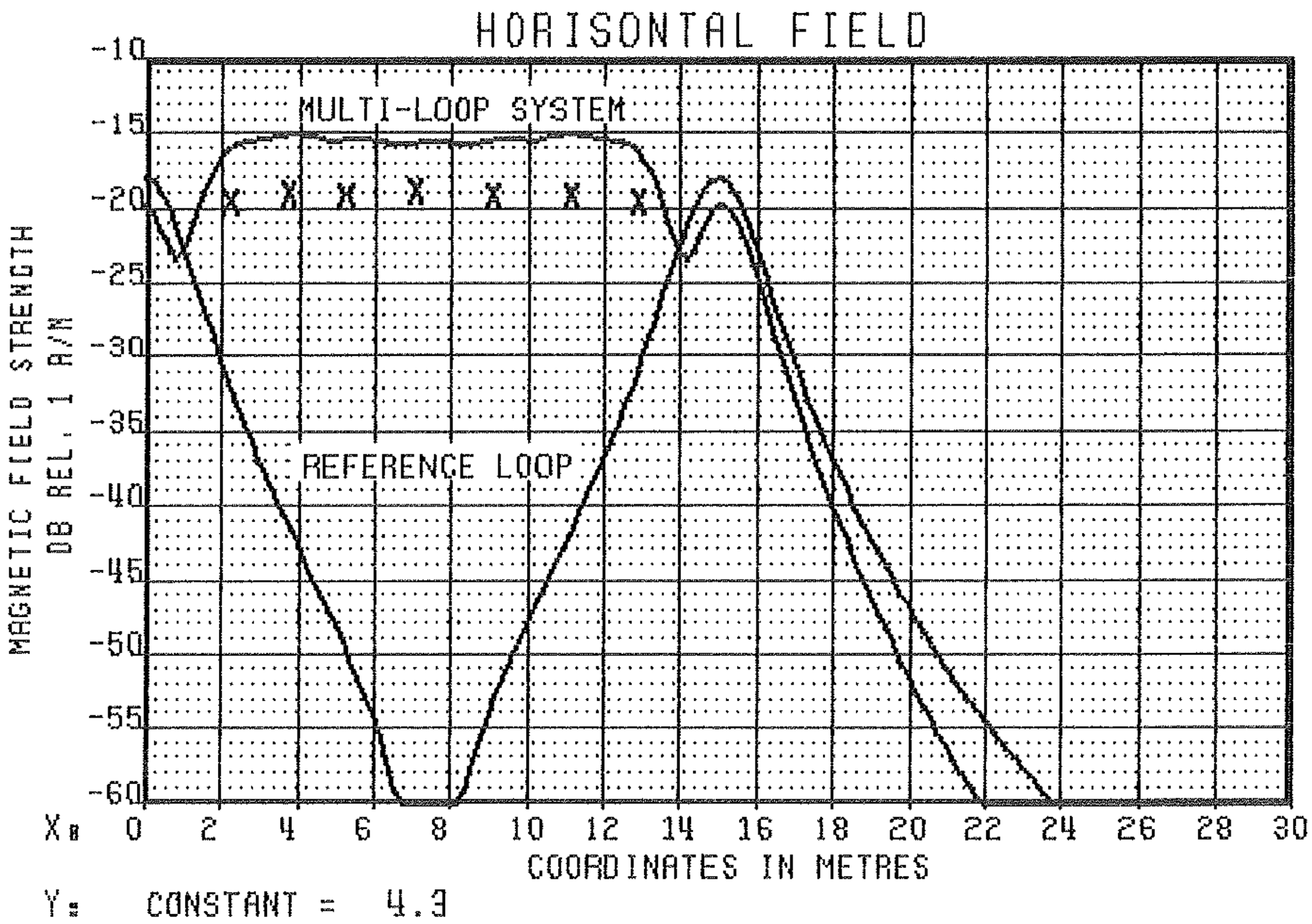


Loop 2: 4 sub-loops (calculated inductance 37 µH/ sub-loop)

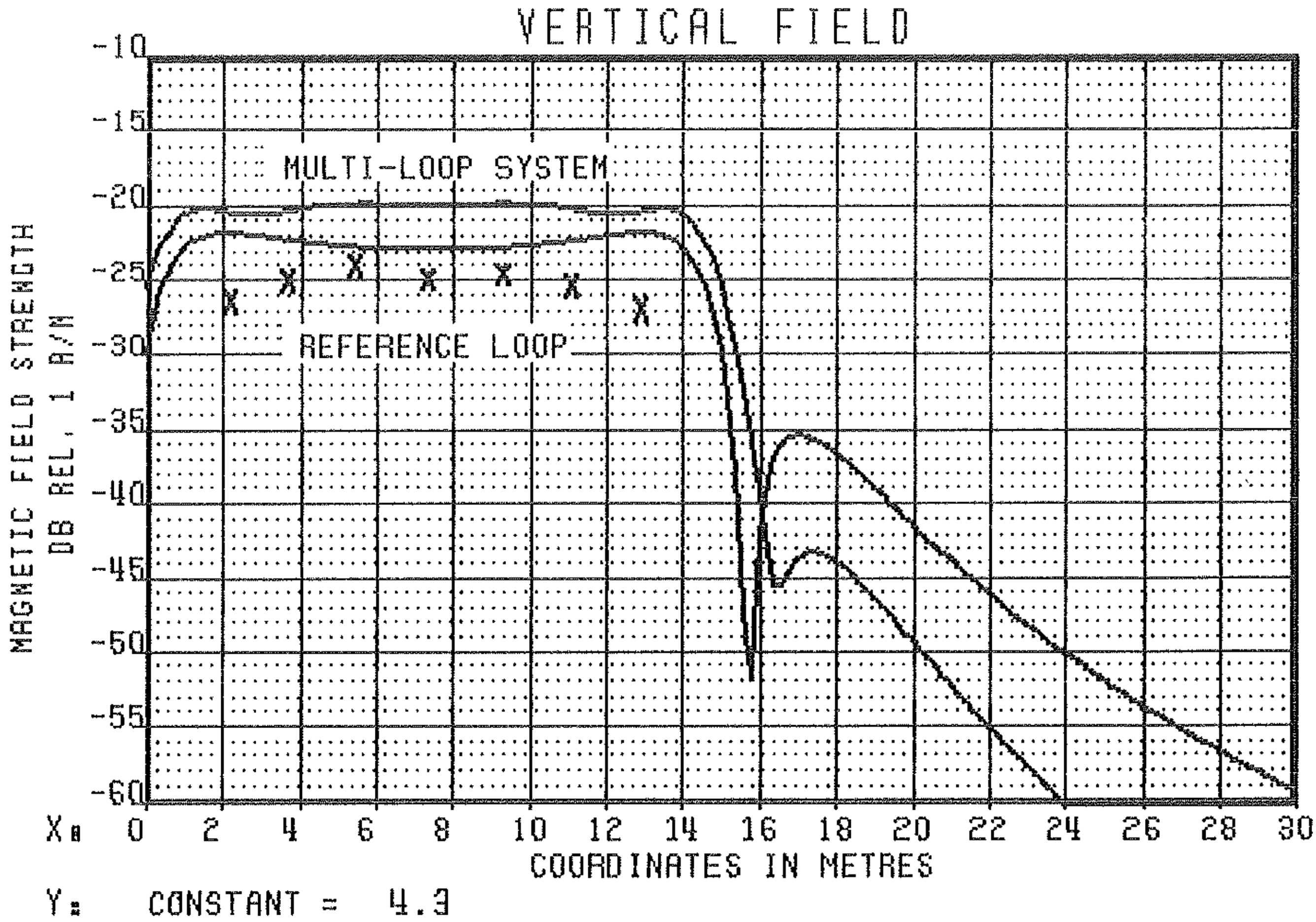


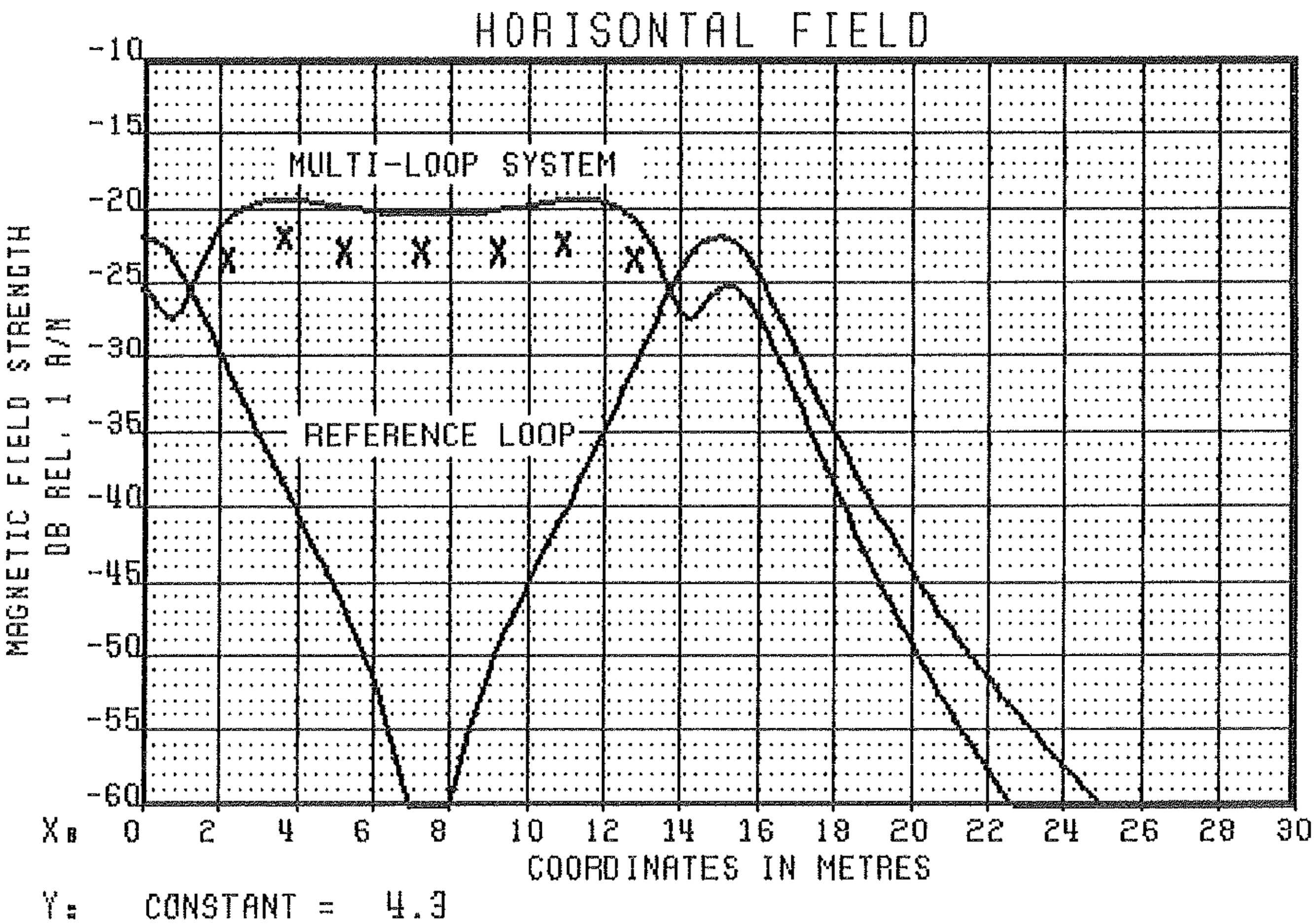
The next three pages show curves of the magnetic field strength for listening heights of 1.20 ,1.80 and 3.80 metres. 3.80 metres listening height corresponds to listening on the next floor above. The crosses indicate measured values for the multi-loop system. Reference curves, calculated for a single loop surrounding the room, are also shown. Calculated inductance for the single loop was 89 µH. All curves were calculated for currents of 1 Ampere.



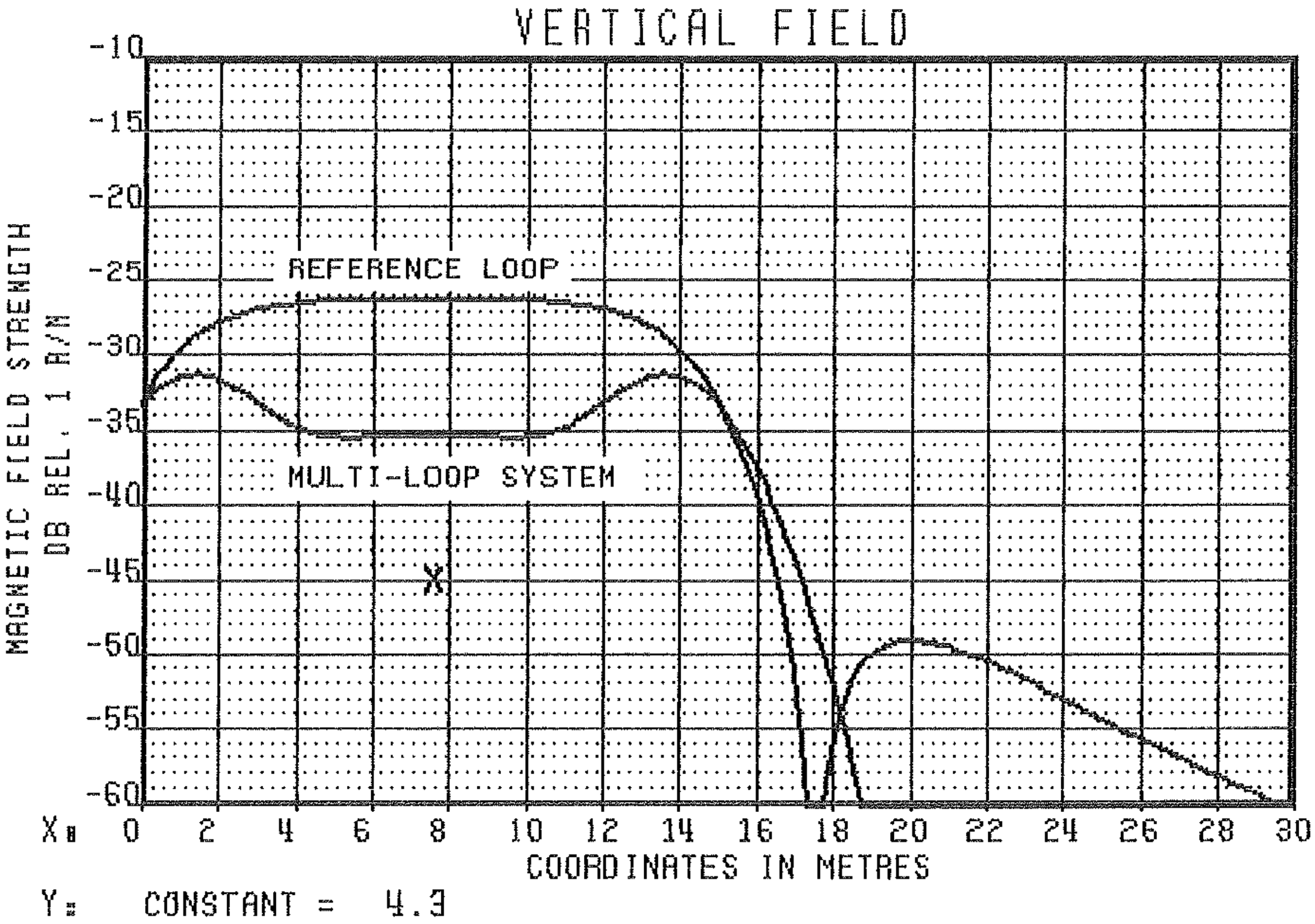


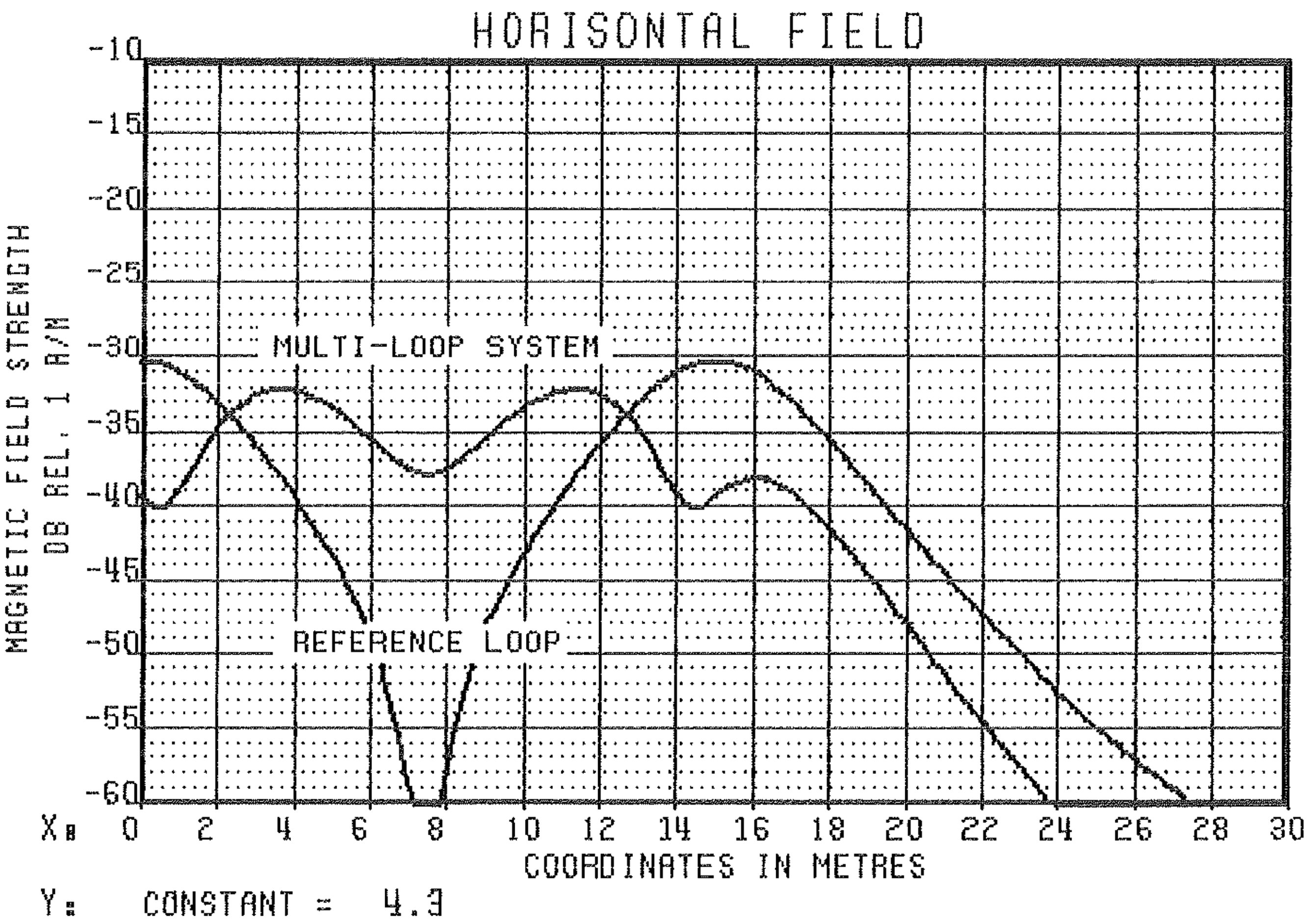
Listening height 1.20 metres.





Listening height 1.80 metres.





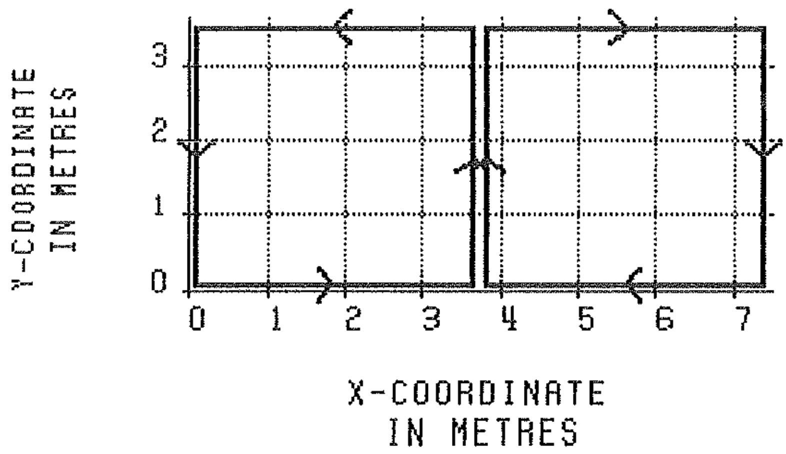
Listening height 3.80 metres.

APPENDIX C:

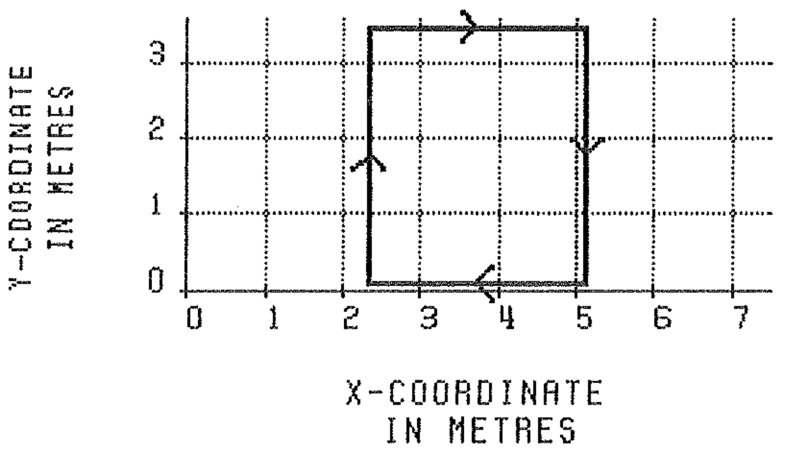
LOOP INSTALLATION IN A SMALL LECTURE ROOM WITH DIMENSIONS 7.50 BY 3.60 METRES.

Loop configurations.

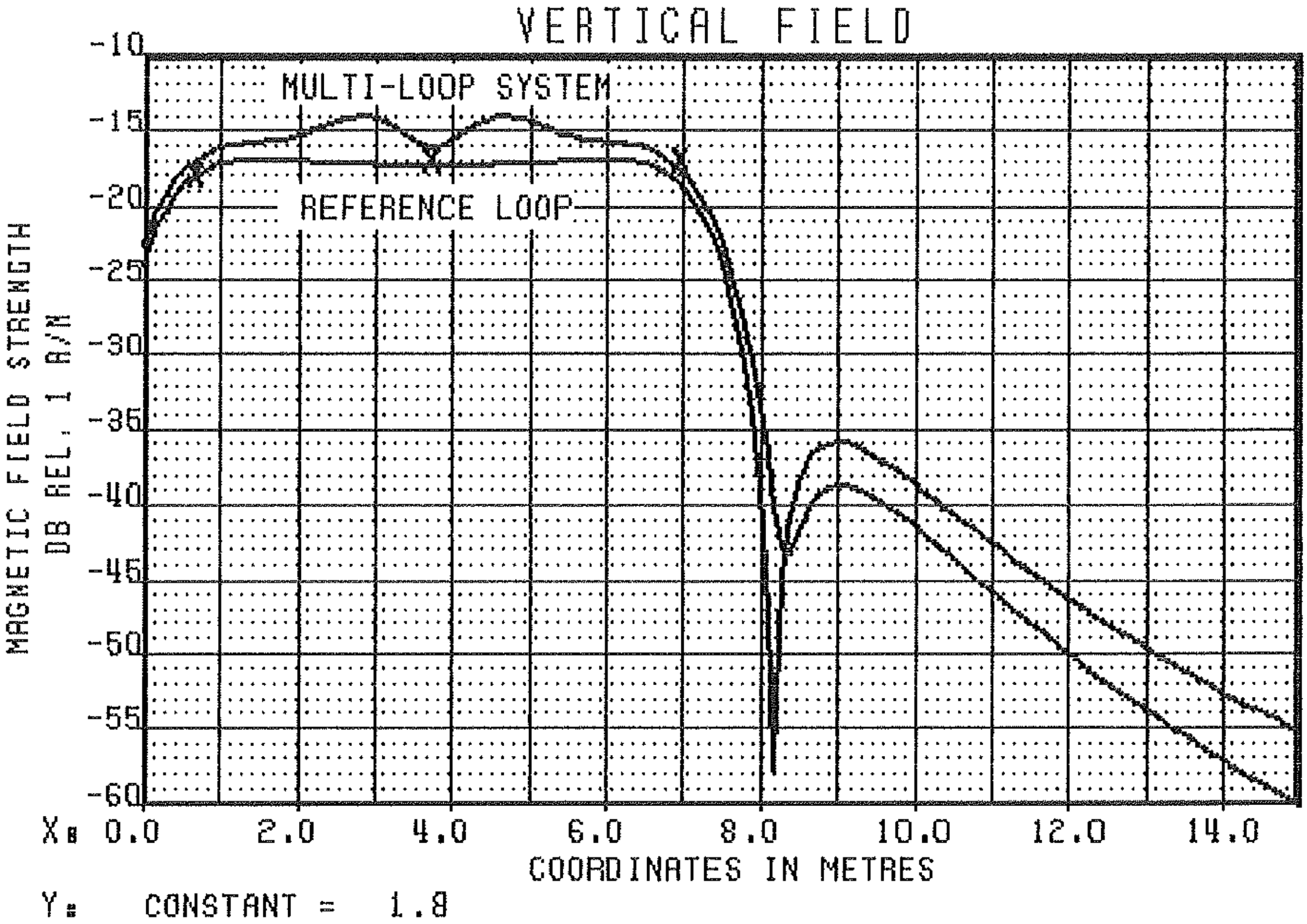
Loop 1: 2 sub-loops (calculated inductance 24 µH/ sub-loop).



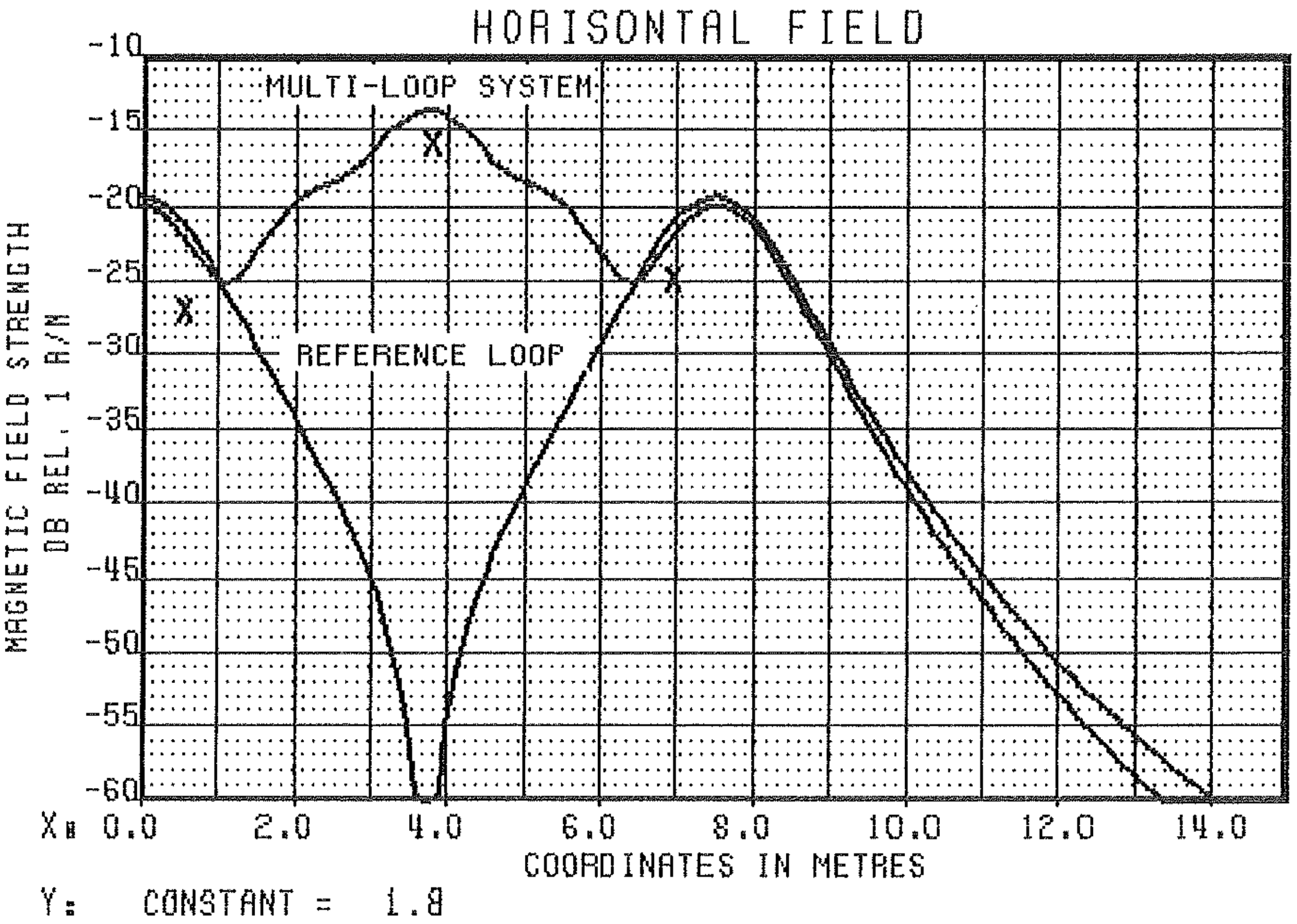
Loop 2: 1 sub-loop (calculated inductance 22 µH).



The next page shows curves of the magnetic field strength for a listening height of 1.20 metres. The crosses indicate measured values for the multi-loop system. Reference curves, calculated for a single loop surrounding the room, are also shown in the figures below for comparison purposes. Calculated inductance for the single loop was 38 µH. All curves were calculated for currents of 1 Ampere.



VERTICAL FIELD
MULTI-LOOP SYSTEM
REFERENCE LOOP
MAGNETIC FIELD STRENGTH
DB REL. 1 A/M
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
X: 0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0
COORDINATES IN METRES
Y: CONSTANT = 1.8



HORISONTAL FIELD
MULTI-LOOP SYSTEM
REFERENCE LOOP
MAGNETIC FIELD STRENGTH
DB REL. 1 A/M
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
X: 0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0
COORDINATES IN METRES
Y: CONSTANT = 1.8

LIST OF REPORTS FROM THE DEPARTMENT OF TECHNICAL AUDIOLOGY, KAROLINSKA INSTITUTET

TA109 1984 Questionnaires on desirable properties of hearing aids.
B Hagerman and A Gabrielsson

TA108 1983 Audio versus audio-visual test - implications for hearing aid frequency responses.
A-C Lindblad, M P Haggard and J R Foster

TA107 1983 Clinical measurements of speech reception threshold in noise.
B Hagerman

TA106 1983 Assessment of perceived sound quality in eighteen High Fidelity loudspeakers.
A Gabrielsson, B Lindström and G Elger

TA105 1982 Detection of nonlinear distortion of speech signals by hearing impaired listeners.
A-C Lindblad.

TA104 1982 Measurement of speech reception threshold - a comparison between two methods.
B Hagerman.

TA103 1981 Problems and methods in judgments of perceived sound quality.
A Gabrielsson.

TA102 1981 Scaling of perceptual dimensions in sound reproduction.
A Gabrielsson, B Lindström.

TA101 1981 Sentences for testing speech intelligibility in noise.
B Hagerman.

TA100 1981 Modulation transfer function and speech transmission index - a method to predict speech intelligibility in Swedish? - The Swedish contribution to the IEC 29B/WG15 multilanguage test.
B Hagerman, A-C Lindblad.

TA99 1980 En metod för subjektiv utvärdering av "kompaktanläggningar".
B Lindström.

TA98 1980 Clinical assessment of perceived sound quality in hearing aids.
A Gabrielsson, B Hagerman, C Berg, A Ovegård, L Änggård.

TA97 1980 Statistical analysis of fricative sounds.
Å Olofsson.

TA96 1980 A method for suppression of periodic noise signals.
S-Å Frykholm, Å Olofsson.

TA95 1980 Hörapparaters frekvenskurvor: IEC-coupler, KEMAR, människa.
U Olsson.

TA94 1980 Some ideas in computerized acoustical impedance measurements.
S-Å Frykholm.

TA93 1979 Assessment of perceived sound quality in high fidelity sound-reproducing systems.
A Gabrielsson, S-Å Frykholm, B Lindström.

TA92 1978 Statistical treatment of data from listening tests on sound-reproducing systems.
A Gabrielsson.

TA91 1978 Taluppfattbarhet för högtalarsystem vid Arlanda utrikesterminal.
B Hagerman, A-C Lindblad.

TA90 1978 A generalization of the concept of total harmonic distortion.
Å Olofsson.

*TA89 1978 Ett programpaket för mätning, syntes och analys av linjära tidskontinuerliga och tidsdiskreta system.
Å Olofsson.

TA88 1978 Reliability in the determination of speech reception threshold (SRT).
B Hagerman.

TA87 1978 Detection of nonlinear distortion in telephone systems.
A Gabrielsson, A-C Lindblad, B Lindström, Å Olofsson.

* indicates that the TA-report is out of stock but is available at a cost of SEK 25.

TA86 1977 Adjective ratings and dimension analyses of perceived sound quality of headphones.
A Gabrielsson, S-Å Frykholm, H Sjögren.

*TA85 1977 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. III.
A Gabrielsson, H Sjögren.

TA84 1977 Automatic gain control and hearing aids. The influence of different attack and release times on speech intelligibility for hearing impaired with recruitment.
T Ahren, S Arlinger, C Holmgren, L Jerlvall, B Johansson, A-C Lindblad, H Sjögren.

*TA83 1976 Detection of amplitude distortion by normal hearing and hearing impaired subjects.
A Gabrielsson, P-O Nyberg, H Sjögren, L Svensson.

TA82 1976 Preferred listening levels and perceived sound quality at different sound levels in "high fidelity" sound reproduction.
A Gabrielsson, H Sjögren.

TA81 1976 Preliminärrapport slingor.
R Ingelstam.

TA80 1975 Emulator för kommunikation mellan minidator typ Honeywell 316 och stordator typ IBM 360.
Bo Jacobsson.

TA79 1975 Mätning av amplitud- och faskurvor för hörapparater med hjälp av minidator.
Å Olofsson.

TA78 1975 Styr- och registreringsenhet för psykoakustisk mätplats.
Å Olofsson, L Persson, H Sjögren.

*TA77 1975 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. II.
A Gabrielsson, H Sjögren.

*TA76 1975 Similarity ratings and dimension analyses of perceived sound quality of hearing aids.
A Gabrielsson, H Sjögren.

*TA75 1974 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. I.
A Gabrielsson, H Sjögren.

TA74 1974 Assessment of comfort and discomfort levels for pure tone, a methodological study.
A Gabrielsson, B Johansson, Bodil Johansson, A-C Lindblad, L Persson.

*TA73 1973 Hörapparaternas driftkostnader.
B Johansson.

TA72 1973 Adjective ratings and dimension analyses of perceived sound quality of sound reproducing systems.
A Gabrielsson, U Rosenberg, H Sjögren.

TA71A 1974 Mätsond för mätning på magnetiska fält inom tonfrekvensområdet.
R Ingelstam.

TA70 1972 Detection of amplitude distortion in flute and clarinet spectra.
A Gabrielsson, H Sjögren.

*TA69C 1975 Some experiments with frequency discrimination for pure tones.
A-C Lindblad, L Åhman.

*TA69B 1972 Continued measurements of frequency discrimination for bands of noise.
A Gabrielsson, B Johansson, A-C Lindblad, L Persson, B Rosenqvist.

TA69 1972 Frequency discrimination for bands of noise.
A Gabrielsson, B Johansson, A-C Lindblad, A Pettersson, B Rosenqvist.

TA68 1972 Judgments and dimension analyses of perceived sound quality of sound reproducing systems. II.
U Rosenberg, A Gabrielsson, H Sjögren.

TA67 1971 Om hörapparatkostnadernas fördelning.
B Johansson.

* indicates that the TA-report is out of stock but is available at a cost of SEK 25.