



BSI Standards Publication

Code of practice for hearing-loop systems (HLS)

National foreword

This Published Document is the UK implementation of IEC TR 63079:2017+A2:2020. It supersedes PD IEC TR 63079:2017+A1:2018 and BS 7594:2011, which are withdrawn.

The start and finish of text introduced or altered by amendment is indicated in the text by tags. Tags indicating changes to IEC text carry the number of the IEC amendment. For example, text altered by IEC amendment A1 is indicated by A1 A1.

The UK participation in its preparation was entrusted to Technical Committee EPL/29, Electroacoustics.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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Published by BSI Standards Limited 2023

ISBN 978 0 539 27651 0

ICS 17.140.50

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 September 2017.

Amendments/corrigenda issued since publication

Date	Text affected
30 September 2018	Implementation of IEC amendment A1:2018
30 April 2020	Implementation of IEC amendment 2:2020
31 July 2023	Correction to supersession details in national foreword

TECHNICAL REPORT



Code of practice for hearing-loop systems (HLS)

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.140.50

ISBN 978-2-8322-4154-7

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CODE OF PRACTICE FOR HEARING-LOOP SYSTEMS (HLS)

FOREWORD

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IEC TR 63079, which is a Technical Report, has been prepared by IEC technical committee 29: Electroacoustics.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
29/917/DTR	29/923/RVC

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

The performance of induction-loop systems is specified in IEC 60118-4, whereas IEC TR 63079 gives recommendations and guidance for their design, planning, installation, testing, operation and maintenance. Provisions for components of a system are given in IEC 62489-1. Methods of calculation and measurement of the magnetic field, in the context of human exposure, are given in IEC 62489-2.

This document takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Any user claiming compliance with this document is expected to be able to justify any course of action that deviates from its recommendations.

CODE OF PRACTICE FOR HEARING-LOOP SYSTEMS (HLS)

1 Scope

This document, which is a Technical Report, gives recommendations for and guidance on the design, planning, installation, testing, operation and maintenance of a hearing-loop system (HLS) intended for communicating speech, music and/or other signals. It is mainly concerned with HLS for hearing enhancement, in which the signals are communicated to users of hearing aids equipped with magnetic pick-up coils.

This document does not apply to induction-loop systems which use a carrier frequency, nor to other systems for hearing enhancement purposes which do not use magnetic induction.

2 Normative references

[A1] The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60118-4:2014, *Electroacoustics – Hearing aids – Part 4: Induction-loop systems for hearing aid purposes – System performance requirements*

IEC 60268-16, *Sound system equipment – Part 16: Objective rating of speech intelligibility by speech transmission index* **[A1]**

3 Terms, definitions, signs and symbols

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 Terms and definitions

3.1.1

hearing-loop system

HLS

system including amplifier(s), microphones and/or other signal sources, in which magnetic fields are created by the flow of audio-frequency current in a conductor arranged in the form of one or more loops or a coil or solenoid

Note 1 to entry: The technical term for a hearing-loop system is "audio-frequency induction-loop system" (AFILS).

3.1.2

HLS for hearing enhancement

HLS in which the intended receivers are hearing aids or specially designed listening devices equipped with coils acting as magnetic antennas

3.1.3

direct-to-reverberant ratio

ratio, at a given point in the sound field, of the sound pressure due to the wanted sound source to the sound pressure due to reverberation

3.1.4

hearing aid

personal amplification system, worn entirely on the listener, which is designed to enable a person with impaired hearing to hear more easily

3.1.5

loop listener

listening device which is designed to give an audible output in response to signals transmitted by an HLS

3.1.6

HLS monitoring receiver

equipment designed to verify the performance of an HLS by audio and visual means

- a) providing visible indication that it is powered and when the strength of the magnetic field produced by the loop falls within a specified range,
- b) providing an audio-frequency output by which the sound quality of the HLS transmissions can be assessed, and
- c) providing other, optional facilities (see Annex A)

3.1.7

magnetic field strength

magnitude of the magnetic field, at a stated point in space and in a stated direction, generated by the flow of alternating current in an HLS

3.1.8

listening plane

plane perpendicular to the axis of telecoils in hearing aids (see Annex B)

3.1.9

useful magnetic field volume

volume within which the system provides hearing-aid users with a signal of acceptable quality

[SOURCE: IEC 60118-4:2014, 3.2, modified — The brackets have been deleted from the definition, as well as the notes.]

3.1.10

system designer

technically competent person who takes responsibility for the technical specification, design and performance of the system

3.1.11

simple system

HLS that is neither large nor complex and does not require specialist skills in order to achieve a satisfactory result

3.1.12

counter system

ticket office system

small area HLS designed to assist communication between (usually) two persons, sometimes through a transparent screen

Note 1 to entry: For example at a ticket office or bank.

3.1.13 complex installation

HLS installation in which any of the following apply:

- HLS that has an approximate coverage area greater than 400 m²;
- it is required to operate close to another HLS, which could lead to co-interference;
- it is required that a certain area is not covered by the HLS, in case it might interfere with sensitive electronic equipment, for example electric guitars or dynamic microphones;
- it is required that the system operates on a number of different listening planes;
- an unconventional layout of loop conductors is indicated;
- there is metal in the building's structure and this causes irregularity in the field strength when using a perimeter loop

Note 1 to entry: Such installations are likely to require specialized design knowledge in order to obtain a satisfactory result.

3.1.14 direction of the magnetic field

resultant direction of the magnetic field at a point in three dimensional space, arising from the phasor sum of components of the field derived by integration over all elements of the induction-loop

3.1.15 HLS reference plane

the plane to which the magnetic characteristics of the HLS are referred when stating specified values

Note 1 to entry The reference plane specification includes its inclination to the horizontal.

3.1.16 reference magnetic field strength level

0 dB reference for magnetic field strength levels, which is 400 mA/m

[SOURCE: IEC 60118-4:2014, 3.1, modified – The definition has been rephrased, and the note has been deleted.]

3.1.17 overspill

magnetic field of usable strength that is present outside the volume in which it is required

Note 1 to entry This magnetic field extends outside the useful magnetic field volume because a field of lower strength than the minimum specified in IEC 60118-4 can still interfere with other nearby HLS or be received with suitable equipment.

3.2 Signs and symbols

3.2.1 Symbol for an induction-loop

The symbol shown in Figure 1 should be used on circuit diagrams to indicate an HLS.

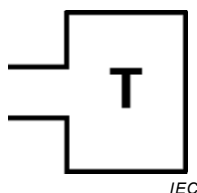
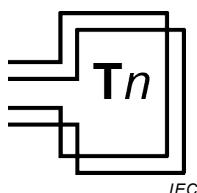


Figure 1 – Symbol for use on diagrams

3.2.2 Symbol for multiple loops

The symbol shown in Figure 2 should be used on circuit diagrams to indicate a complex or low-spill HLS.



NOTE *n* is the number or letter corresponding to the classification of loop. See Clause 11.

Figure 2 – Symbol for multiple loops for use on diagrams

3.2.3 Sign for display in premises where an HLS is installed and for HLS equipment identification

Signs for display should be produced on a durable material.

Areas where the reception of the HLS is satisfactory should be clearly indicated at visible positions by means of the sign shown in Figure 3, which is based on the one originally adopted by the World Federation of the Deaf. The sign should indicate T as shown. The background colour should be Pantone reference 661 or 662 (blue) and the printing should be in white.

NOTE Some organizations that support people with hearing loss do not approve HLS unless signs are displayed. Signs of other colours are found in use.

Normally the dimensions of the display signs should be a minimum of 100 mm × 100 mm; when used on equipment, they can be of any convenient size.

The sign should appear at a position visible in normal use on HLS equipment, on loop cable junction boxes and adjacent to the loop cable itself where it would be helpful to maintenance personnel or help to prevent accidental disturbance.



Figure 3 – Sign for display in premises to indicate that an HLS is installed and for HLS equipment identification

3.2.4 Identification of areas where reception of the HLS is not satisfactory

Areas where the reception of the HLS is not satisfactory should be clearly indicated on a plan of the space by means of the sign shown in Figure 4. The plan should be placed where it can be seen by both hearing-aid users and staff. This sign should also be placed visibly in the unsatisfactory area and/or on all seats in that area.

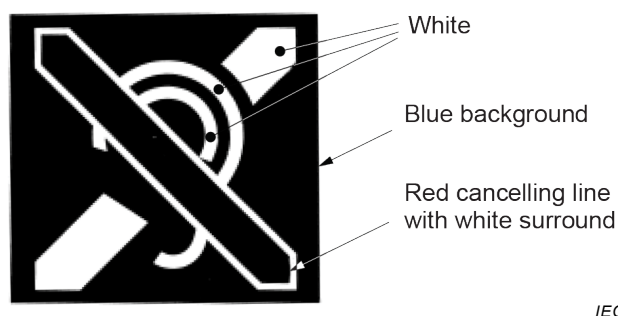


Figure 4 – Sign to show seating areas where HLS reception is not satisfactory

4 General

4.1 How to use this document

4.1.1 Persons addressed

This document is divided into clauses, with recommendations intended primarily for

- purchasers of HLS (Clauses 1 to 9, 20 and Annex B),
-  designers of HLS and HLS equipment (Clauses 9 and 10, 20, Annex A, Annex C to Annex G and Annex J), 
- installers of HLS (Clauses 11 to 17, Annex A and Annex H),
- those responsible for commissioning, testing, operation and maintenance (Clauses 14 to 18, 20 and Annex H), and
- those responsible for day-to-day operations, ensuring that the facilities are accessible to as many people as is reasonably possible (Clauses 19 to 21, Annex A and Annex B).

4.1.2 Objectives

The recommendations of this document are intended to lead to the following.

- a) Prospective purchasers clearly understand the functions and limitations of an HLS (see Annex B).
- b) The design, installation and setting-up of the HLS allows compliance with the appropriate requirements for safety and electromagnetic compatibility and all relevant regulations relating to electrical installations.
- c) Users wearing hearing aids equipped with a magnetic pick-up coil receive signals transmitted by the HLS that are intelligible and free from undue distortion and interference even when all non-HLS equipment normally used in the environment is in operation.
- d) The reception of such signals is possible in any part of the space; where, by force of circumstance, the reception in some parts is limited, this is clearly defined and identified (see 3.2.4).
- e) Visual indication is given to prospective users that an HLS is installed.
- f) Means are provided for the building management to easily verify that an HLS is working satisfactorily (see Annex A).
- g) The HLS can be satisfactorily operated and maintained by properly trained and competent personnel.
- h) Where necessary, the HLS is arranged for minimum extraneous coverage. It should be understood, however, that even if an HLS is designed to limit extraneous coverage, it might be possible for a determined person outside the intended area of coverage to receive what might be confidential information.

Guidance is given on means to reduce possible effects of the magnetic field produced by the loop on other nearby equipment.

4.2 Specialist advice

Except for home systems sold as a complete kit, the engagement of a skilled system designer is advisable and is considered to be essential whenever large or complex installations are involved. Professional bodies can be approached for lists of such specialists.

4.3 Safety aspects

It is essential that an HLS, even if temporary, is installed in a safe manner and in accordance with safe work practices (see 10.7).

4.4 Conforming to existing performance documents

The performance document for HLS is IEC 60118-4, the requirements of which have been incorporated (where applicable) as recommendations in this document.

5 Technical advice

5.1 Complying with this document

Significant problems can arise with poorly designed or installed HLS. Purchasers should stipulate that the design and installation are to comply with this code of practice and that the system should conform to IEC 60118-4. Operation and maintenance procedures should also be in accordance with this code of practice.

NOTE For small self-install systems intended for home use, it is expected that the manufacturer has ensured that the basic requirements of this document will be met if the user follows the installation instructions carefully.

It is recommended that contracts include a specific variation clause under which parties agree to the terms of the contract and document any agreed variations.

5.2 Seeking technical advice

While many successful HLS have been installed to date, compliance with this document should greatly increase the probability that satisfactory results will be obtained. Its provisions, however, cannot be properly applied without adequate technical knowledge and experience, and each design presents individual challenges.

Wherever possible, technical advice should be sought during the early planning stages of an HLS. Such advice should cover

- a) the suitability of an HLS for a particular venue and/or application (see Clauses 6 and 9),
- b) factors that can adversely affect the performance of an HLS,
- c) factors that can add to the cost of installing an HLS,
- d) the need for, and scope of, an initial site assessment (see Clause 7),
- e) details of the audio source(s) (see Clause 10), and
- f) where microphones are to be used, their positioning to minimize extraneous noise and reverberation (see Clause 10).

In all cases, the responsibility for the correct performance of the system at the time of commissioning should lie with the system designer. It should be understood, however, that the system designer cannot be held responsible for the parts of the system outside their control.

Where the HLS is to be installed as part of other electrical works, it is especially important that all aspects of the design are clearly specified, especially regarding microphones, required coverage and overspill.

5.3 The nature of the advice

Advice sought will depend on the particular installation requirements for each HLS, but should generally be covered by the following categories:

- a) advice from the designer/installer direct to the client on all aspects, from initial quotations for the task in the planning stages through to installation, commissioning and maintenance of the HLS;
- b) advice from the designer to a technician who lacks experience with HLS installations but who has the task of installing the system (e.g. systems in new buildings where installation is to be carried out by electrical contractors; systems installed by in-house staff);
- c) advice from an appropriate organization or professional body.

5.4 Professional (consultancy) advice

Professional advice from a specialist consultant should be sought when installations are to be undertaken in extra-large buildings, prestigious buildings and those posing special difficulties.

The advice of an independent consultant can also be sought in the event of a dispute between the purchaser and supplier or manufacturer. Such advice can often provide the most economical resolution of the dispute.

6 Purpose of the system

The most fundamental purpose is to help people to hear, not to meticulously obtain readings on meters; these are a method of achieving the desired result.

Before approaching a supplier, it is important to write down, in non-technical terms, what the users of the system require it to do and the environment it is to be used in. Care should be taken that this is as comprehensive as possible: anything left out at this stage can result in extra expenditure later.

Factors that should be considered include

- a) the room(s) and three dimensional space(s) to be covered,
- b) what sounds or audio signals are to be reproduced and where they will come from (all the sources and places),
- c) whether the audio information needs to be confidential (e.g. a court),
- d) known/likely interference from other equipment (e.g. power transformers, air-conditioning equipment, other HLS, and some fluorescent lighting),
- e) building construction, such as structural steel work and metal in walls, floors and ceilings, particularly close to the looped area,
- f) any metal construction within the space (e.g. tiered seating or metal suspended ceiling grids), and
- g) architectural considerations or restrictions (e.g. listed building status).

7 Choosing the system supplier

7.1 General

Possible procedures for acquiring an HLS are recommended in 7.2, 7.3 and 7.4. The choice of procedure should depend on the size of the space to be covered and any special complications which might be involved. Advice can be obtained from organisations that care for people who are deaf or have hearing impairment.

7.2 Approaching a contractor

Particularly for a simple HLS, a contractor should be asked to conduct an initial site survey (see IEC 60118-4), design, supply and install suitable equipment and all cabling. Responsibility for choosing appropriate equipment (microphones, amplifier, monitoring device, etc.) and for installing and setting up the HLS correctly should rest with the contractor.

NOTE For a small HLS, the cost of a formal initial survey might not be justified, but many contractors will conduct an informal survey as a matter of course.

7.3 Approaching a manufacturer of HLS equipment

Some manufacturers of HLS equipment and their local representatives are willing to produce the site survey for the proposed installation, design a system and, perhaps, recommend a competent installation contractor. Manufacturers who are unable to provide this service themselves might offer contact with appropriate designers/installers who can undertake such projects.

Responsibility for choosing appropriate equipment (microphones, amplifier, etc.) and commissioning the system should rest with the selected manufacturer or designer/installer. The contractor should be responsible to the manufacturer for the correct installation of the HLS and commissioning (where this is also undertaken).

For some HLS, the installation contractor might call in a manufacturer to provide detailed technical advice on areas of uncertainty or particular difficulty. On these occasions the contractual obligations of the installation contractor and the manufacturer to the prospective purchaser should be clearly documented, preferably under a single contract.

7.4 Approaching a specialist consultant

When it is appropriate to engage a specialist consultant, this should be done at the earliest opportunity. The consultant should be responsible for the initial survey, design and commissioning of the HLS, choice of equipment and for helping to assess installers' proposals. Where necessary, the consultant should also liaise with architects and construction

contractors on matters affecting the HLS. Names of consultants who specialize in this work can be obtained from professional associations.

NOTE Such a consultant might be independent or might be a competent person employed by a manufacturing or contracting organization.

8 Contractual provisions

8.1 Performance specification

The purchase contract should include an agreed performance specification, prepared by the system designer, to which the system is contractually required to conform at the commissioning stage. Where the choice of equipment to be used is not completely under the control of the system designer (for example, if some existing microphones are to be used), any reservation about the suitability of such equipment should be clearly explained to the purchaser in writing.

8.2 Verifying that the completed system delivers its intended performance

Tests of the completed installation to verify that the HLS performs satisfactorily should be specified in the contract and should cover

- a) checks of the system using a meter designed to measure field strength in conformity with IEC 60118-4,
- b) subjective tests using persons with normal hearing listening through suitable receiving units,
- c) subjective tests by hearing aid users, with their hearing aids set to T, and
- d) provision of either field-strength meters for use by trained staff or a fixed monitor receiver.

If the subjective tests are conducted correctly and do not provide confirmation of positive instrumentation checks, the system designer should be held responsible for identifying measures necessary to achieve satisfactory results. The contract should, therefore, include adequate provisions for properly defining the system designer's responsibility with regard to the preparation of any required remedial proposals and their implementation.

NOTE The emphasis is on satisfactory results, as determined by the users of the system, rather than achieving particular objective results from technical tests. See IEC 60118-4.

The system designer should advise on methods of eliminating interference by the HLS with other nearby electronic equipment, and modifications to the HLS should be agreed with the system designer; it is advisable for the contract to specify how the costs of such remedial work are to be apportioned.

It might be impossible to predict before the HLS is installed and tested the need for specific measures to eliminate interference by the HLS with other nearby electronic systems (e.g. multiple grounding, legacy equipment with inadequate immunity, unforeseen proximity of loop cabling to other cabling – see 10.9).

Remedial work should normally be carried out by the body having technical responsibility for the appropriate system (telephone systems, etc.).

The tests in Clause 14 are to determine the perceived sound quality of the system and its adequate freedom from noise, reverberation and distortion. They are not intended to demonstrate that the needs of any particular hearing-aid user are met.

8.3 Arbitration

It is recommended that provision is made in the contract for arbitration in the event that problems arise. Where possible, an arbitration body should be identified.

9 Classification of systems

Because of the diversity of use for HLS, the following classifications are intended to group similar applications, providing minimum performance characteristics for each group based on the intended use; for example, the permissible magnetic noise and overspill with adjacent counter loops can be considerably higher than that of a theatre system as the user is only in contact with the counter system for a small period of time.

HLS should be assessed by a competent person and assigned one of the following classifications for operation and performance.

- a) Portable or hand held self-contained equipment. This equipment is designed for mobile/temporary use only to assist one-to-one communication. It is not intended to be used on counters or left permanently installed in a location. It should be understood that such systems have very limited performance, for example the coverage rarely exceeds 0,5 m from the equipment or its microphone.
- b) Small volume systems, for use in counters, signage, intercom, emergency voice communication system. Coverage is required within a small defined volume (generally not more than 2 m × 2 m × 0,5 m), where the user is in a fixed position and use is transitory, for example counter systems for a ticket office, reception desk, help points or disabled refuges. For counter systems where confidentiality is important, the design of the HLS can be required to attenuate the magnetic field outside a designated space (usually the useful magnetic field volume) to a level at which speech cannot be understood. But it is not necessary for the magnetic attenuation to exceed the acoustic attenuation.
- c) Perimeter loop systems, for coverage of a single volume where other HLS are not present in the vicinity and where security, overspill or overcoming significant metal losses is of no importance, for example church/stone building remote from other buildings containing HLS.
- d) Mobile loop systems, for temporary use as a perimeter loop in a relatively small space, where other HLS are not present in the vicinity and where security, overspill or overcoming significant metal losses is of no importance, for example a system that provides a loop of 50 m perimeter.
- e) Multi-loop systems, specifically designed to control the horizontal and vertical field components for HLS installed in close proximity and/or to overcome significant metal content, for example classrooms or cinemas with multiple HLS, an auditorium with a box office HLS in same building, reinforced concrete construction, or an office space with a raised steel computer floor. The techniques involved depend entirely on the individual application: from as simple as a figure-of-8 loop, to the use of separate arrays of loops in conjunction with a phase shifter or similar device. Consultation of a specialist in system design is essential to ensure that the correct solution is applied. Professional associations can be approached for lists of such specialists.
- f) Loop systems designed for purposes other than assistive listening such as stage direction or observational counselling.
- g) Body worn loops, such as neck loops and ear-hooks (also known as silhouettes).
- h) Specialist loops which fall into none of the above categories, such as systems for lifts (elevators), which generally require detailed design work by a competent HLS specialist.

Table 1 gives the required features, performance and indications for different loop classes and covers the desired and minimum features of some classes; by their nature the other classes have specific requirements beyond the scope of this document.

Table 1 – Classes of loop system

Class	Allowable background noise	Field variation in the useful magnetic field volume	Loop separation ^a	Indications
	dB (0 dB = 400 mA/m)	dB		
Portable or hand held self-contained equipment	–32, –22 for short time periods	12	2 m	Power
Small volume system		12	Width of loop × 2 e.g. 2 m for counters using 1 m wide loop	Power, loop current, input signal present or automatic gain control active
Perimeter loop systems	–32, –22 for short time periods (for critical listening systems, for example auditoria, as close as possible to –47)	6	Width of loop × 2 e.g. 10 m for 5 m wide loop	
Mobile loop systems			As specified by the designer	
Multi-loop systems				
Body worn loop systems		Not applicable	Not applicable	Power
Specialist loops	As specified by the designer			

^a Separation between two adjacent loops in the plane of the loops to minimize the pick-up of signals from one loop by a hearing-aid user using the other loop. Where loops are installed in rooms one above the other, the situation is more complex and requires specialist knowledge to minimize interference.

10 Design

10.1 General

Many successful HLS designs have been produced but because of the proliferation of less-than-satisfactory design methods and general uncertainty, an in-depth treatment of verified design procedures is given here. Detailed derivations of the design formulas, and further information, are given in 10.4 and Annex C.

All values of alternating voltage, current and magnetic field strength are RMS values unless otherwise stated.

An HLS should be designed to provide the following.

- A sufficiently (but not excessively) strong, and uniform (useful) component of magnetic field within the required working area, without producing an unacceptably extended coverage area which could cause interference with other systems or compromise confidentiality.
- Usually, the plane of the loop is horizontal and only the vertical component of the magnetic field is effective. If some of the hearing aid users are lying down, such as in hospital, the loop plane should not be horizontal. A special loop system could alternatively be installed. In general, the component of the magnetic field parallel to the axis of the magnetic pick-up coil in the hearing aid is the effective component.
- The magnetic field strength in item a) over the frequency range 100 Hz to 5 kHz (see IEC 60118-4) with acceptable uniformity and amount of non-linearity distortion.

Normally, the system should be designed to have an overall frequency response (measured as magnetic field strength) which is –3 dB at 100 Hz and 5 kHz relative to the value at 1 kHz, and is as flat as practicable between these frequencies.

The factors relevant to item a) are the dimensions of the loop, the number of turns and the current flowing in it, and the perpendicular distance between the loop and the listening plane. Apart from the characteristics of the microphones or other signal sources and the amplifier(s), the major factor relevant to item b) is the effect of the impedance/frequency characteristic of the loop on the variation with frequency of the current flowing in it. This document considers several ways of achieving a sufficiently low variation with frequency.

10.2 Symbols

For the purposes of this document, the following symbols apply.

A	length of the side of a square loop or of the shorter side of a rectangular loop, expressed in metres (m)
B	length of the longer side of a rectangular loop, expressed in metres (m)
D	length of the diagonal of a loop, expressed in metres (m)
d	diameter of the loop conductor, expressed in metres (m)
f_c	frequency of the upper limit of the loop pass band, expressed in hertz (Hz)
H	RMS magnetic field strength, expressed in amperes per metre (A/m)
H_o	RMS magnetic field strength at the centre of the loop and in its plane, expressed in amperes per metre (A/m)
H_{oz}	perpendicular component of the RMS magnetic field strength at a point, distance z from the plane of the loop along the perpendicular through the centre of the loop, expressed in amperes per metre (A/m)
h	height of the telecoil above or below the plane of the loop, expressed in metres (m)
NOTE The usual case where the plane of the loop is horizontal is assumed.	
h_n	height ratio, $2h/J(AB)$ for a rectangular loop
I	RMS current in the loop conductor, expressed in amperes (A)
K	direct to reverberant sound pressure level ratio, expressed in decibels (dB)
L	inductance of the loop, expressed in henrys (H)
n	number of turns in the loop
R	resistance of the loop, expressed in ohms (Ω)
r_n	resistance ratio ($R/\omega_c L$)
V	RMS voltage between the ends of the loop conductor, expressed in volts (V)
Z	impedance, expressed in ohms (Ω)
α	temperature coefficient of the resistivity of copper (wire), $3,93 \times 10^{-3} K^{-1}$
γ	aspect ratio = B/A
θ	temperature, expressed in degrees Celsius ($^{\circ}C$)
μ_0	magnetic permeability of space, expressed in microhenrys per metre ($0,4 \mu H/m$)
ρ_0	resistivity of copper (wire) at $0^{\circ}C$, expressed in nano-ohm metres ($16,5 n\Omega \cdot m$)
ω_c	angular frequency of the upper limit of the loop pass band, expressed in radians per second (rad/s)

10.3 Basic theory

10.3.1 Production of a magnetic field

Current flowing in a conductor in the form of a loop produces a magnetic field in the space inside and surrounding the loop. A pictorial representation of this field, in the form of "lines of force", is shown in Figure 5.

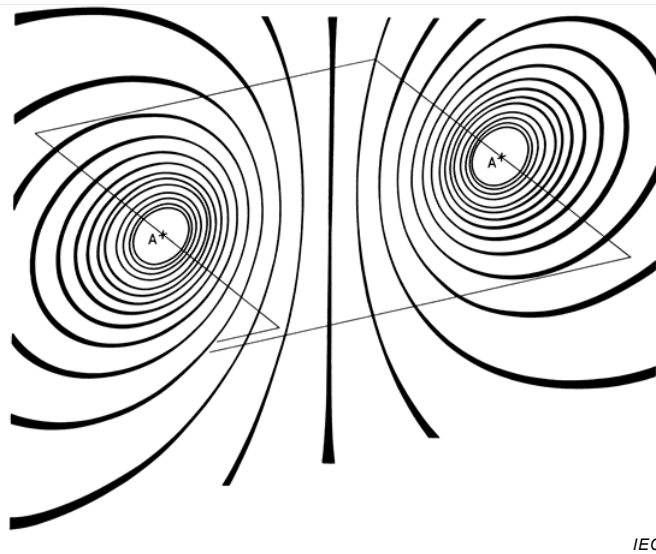


Figure 5 – Pictorial view of the magnetic field (lines of force) of a rectangular loop

The loop has an impedance which can be represented by a resistance and an inductance in series. For a single turn, rectangular loop, using a solid (not stranded) conductor, the following formulas apply.

The value of the current (in A) is given by:

$$I = \frac{\pi ABH_0}{2D} \quad (1)$$

The value of the resistance (in Ω) is given by:

$$R = \frac{8\rho_0(1+a\theta)(A+B)}{\pi d^2} \quad (2)$$

The value of the inductance (in H) is given by:

$$L = \left\{ \frac{\mu_0(A+B)}{\pi} \right\} \ln \left\{ \frac{A+B}{d} \right\} \quad (3)$$

These formulas are derived in Clauses C.1 to C.3. In most cases, an actual loop can be represented with sufficient accuracy by a plane rectangular loop of the same overall dimensions. Deviations from the plane (such as might be needed to negotiate doorways) increase the inductance by approximately half as much as would be expected from the increased length, but have full effect on the resistance. If the loop shape is approximately circular, or more complex (for example cruciform), the methods indicated by Dalsgaard 0¹, by Grover 0 and in C.1 to C.2 can be used to calculate the current required for a given field strength, resistance and inductance.

¹ Numbers in square brackets refer to the Bibliography.

While the values calculated with Formulas (1) to (3) (or with the simplified versions, Formulas (7), (8) and (9)) are normally in close accordance with measured values, the resistance and inductance of both trial loops and installed loops should be measured. Unpredicted effects, such as those due to conducting and/or magnetic materials or caused by work hardening due to flexure of the loop conductor, might make the measured values significantly different from those calculated. The measurement might require the use of a bridge specially designed for measuring low values of inductance with high resistive losses. A measuring frequency of 5 kHz or even 10 kHz helps to avoid errors. It is essential that the *series* equivalent inductance and resistance are measured or calculated, not the *parallel* equivalent.

10.3.2 Directional pattern of the magnetic field

The magnetic field varies in both strength and direction within and outside the loop. At the centre of the loop, the field strength is at its lowest value within the loop, and is directed perpendicular to the plane of the loop.

In most hearing aids, the axis of the telecoil is approximately vertical when the user is standing (or sitting). The output voltage of the telecoil is therefore proportional to the vertical component of the magnetic field:

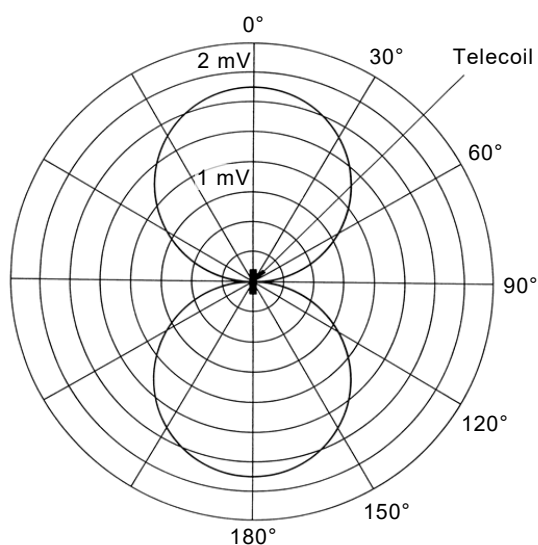
$$V = kH\cos\varphi$$

where

φ is the angle between the direction of the magnetic field and the axis of the telecoil;

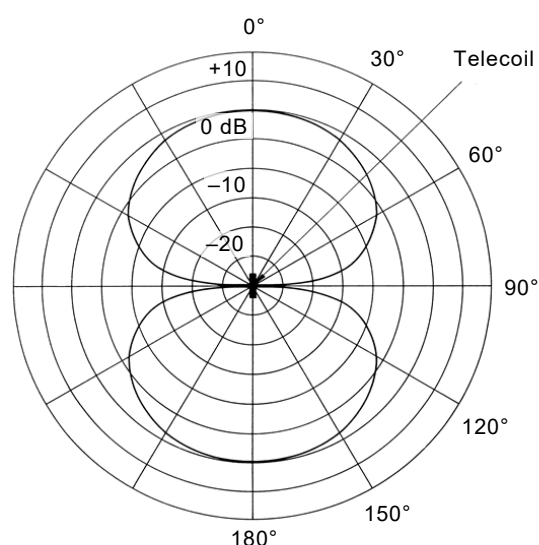
k is a constant.

The resulting directional response of the telecoil is shown in Figure 6. It should be noted that the response is reduced by only 3 dB at $\hat{I} = 45^\circ$ and by 6 dB at $\hat{I} = 60^\circ$. If the axis of the telecoil is nearly perpendicular to the direction of the magnetic field, the response is greatly reduced. This occurs, for example, if the telecoil is nearly vertically above or below the conductor or a horizontal loop, where the direction of the magnetic field is horizontal. There is evidence that in some hearing aids the directionality of the response of the telecoil is greater than predicted above, probably due to the presence of metal near the coil. It is therefore desirable that the plane of the loop should be horizontal, or nearly so, if the coverage area has a horizontal floor and the hearing aid users are standing or sitting.



Axis of telecoil in 0° to 180° direction.
The voltage values are typical.

IEC



Axis of telecoil in 0° to 180° direction.

IEC

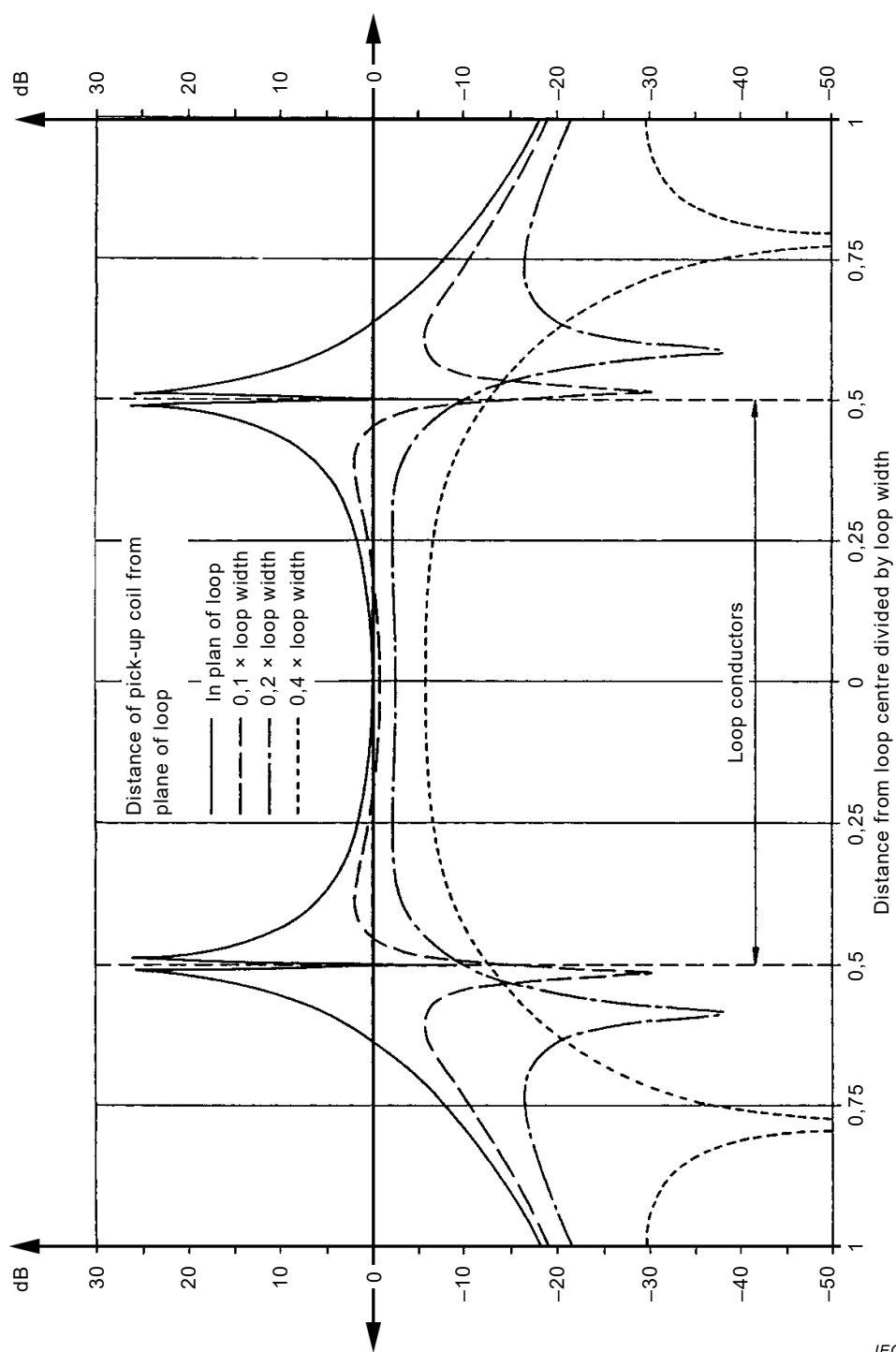
a) Plotted on a linear amplitude axis

b) Plotted with amplitude in decibels
(logarithmic axis)

Figure 6 – Directional response of a hearing aid telecoil

The average height of the telecoil above the floor can be taken as 1,4 m when the hearing aid users can be standing or sitting. For small loops (where the height affects the performance more significantly), and/or where the users can be in other attitudes (such as lying in hospital beds), a closer estimate of the actual average height is required. In the latter case, the plane of the loop (or, perhaps, of part of the loop) should clearly not be horizontal.

The variation of the magnetic field strength is quite large in the plane of the loop. In particular, the strength becomes very great close to the loop conductor, and this can cause disturbance to hearing aid users. A more uniform field strength, both in terms of the total field and of the perpendicular component, is obtained above or below the plane of the loop (see Figure 7).



NOTE The full line shows the perpendicular component and the dashed line shows the coplanar component of the field.

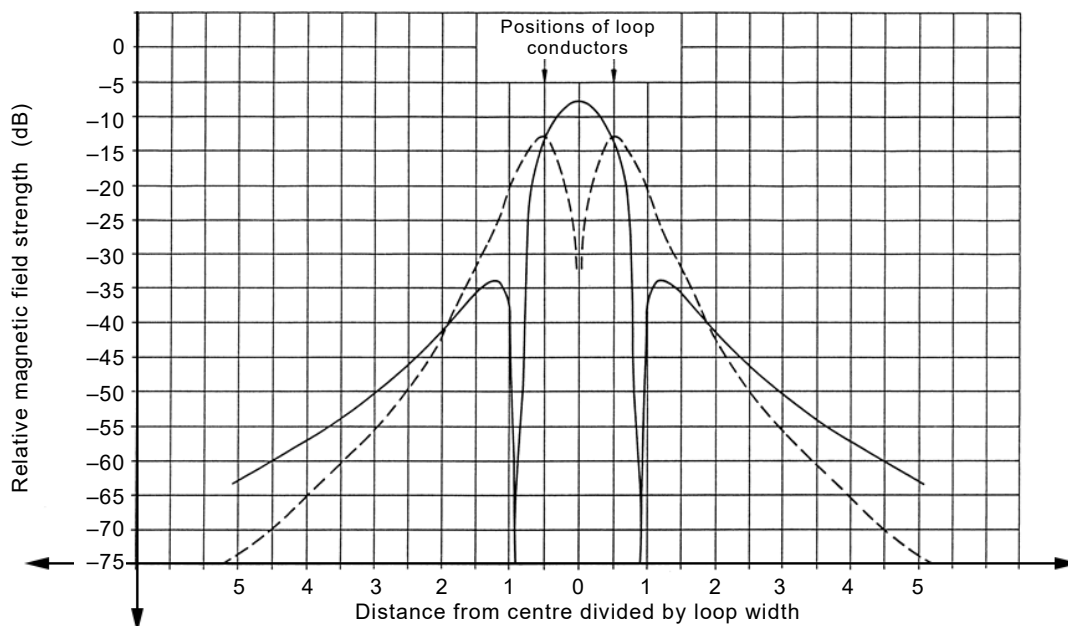
Figure 7 – Variation of the strength of the perpendicular component of the magnetic field across an axis of a rectangular loop, with listening height as parameter

Care should be taken to distinguish between the total field strength and its coplanar and perpendicular (normally horizontal and vertical) components, since their variations within and outside of the loop are quite different (see Figure 7, Figure 8 and Figure 9).

NOTE 1 In the plane of the loop, the direction of the magnetic field is perpendicular to the plane.

NOTE 2 In the areas A immediately surrounding each conductor, the lines of force continue to crowd together, representing a stronger field.

NOTE 3 At certain points, above and below each conductor, the direction of the magnetic field is parallel to the plane of the loop. Normally, at these points, a hearing aid produces no output. For normal listening heights, the points are outside the perimeter of the loop.

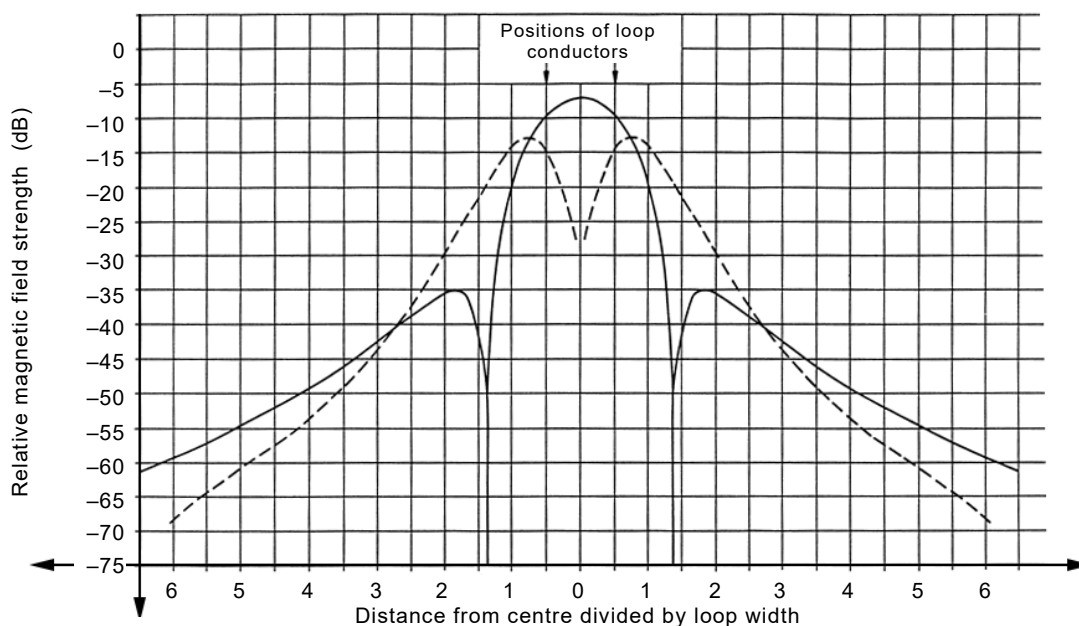


The direction of the coplanar component is along the median, and the field strengths are referred to the field strength at the centre of the loop and in its plane as 0 dB.

IEC

NOTE The full line shows the perpendicular component and the dashed line shows the coplanar component of the field.

Figure 8 – Variation across the median of a square loop of the perpendicular and coplanar components of the magnetic field at a height ratio $h_n = 1$



The direction of the coplanar component is along the diagonal, and the field strengths are referred to the field strength at the centre of loop in its plane as 0 dB.

IEC

Figure 9 – Variation across the diagonal of a square loop of the perpendicular and coplanar components of the magnetic field at a height ratio $h_n = 1$

10.3.3 Uniformity of the magnetic field strength

The problem of disturbance of hearing aid users due to the high field strength near the loop conductor could occur if the loop were at head-height (or chest-height, for body-worn aid users) for either seated or standing listeners, and where the listeners could approach the loop conductor closely. This should be avoided by installing the loop either at or below floor level or well above head-height, thus giving an even more uniform field than is achieved with the loop nearer the listening plane, but requiring more current in the loop for the same field strength at the listening position.

It can be shown (see Clause C.1) that a height ratio h_n (termed "relative listening height" by Dalsgaard) of 0,14 gives reasonable uniformity, for all likely values of aspect ratio of the loop, but the resulting distance from the plane of the loop to the listening plane might be too large to be practicable if the loop is large (for example 3,7 m for a square loop of 50 m side). In such a case, a suitable multiple loop layout can be used. This can reduce the actual listening height required, for a given degree of uniformity, to that required for each sub-loop considered separately.

The separation of the listening plane from the loop plane reduces the field strength at all points of the listening plane. At the centre of the projection of the loop on to the listening plane, i.e. at the loop reference point, the reduced field strength H_{0z} , for a square loop, is given by the following formula:

$$\frac{H_0}{H_{0z}} = \frac{(1 + h_n^2) \sqrt{(2 + h_n^2)}}{\sqrt{2}} \quad (4)$$

The derivations of this formula and of the analogous expression for a rectangular loop of aspect ratio γ are given in Clause C.2, and values of H_0/H_{0z} with γ as parameter are given in Table C.1. The field strength due to a square loop falls off more slowly with distance than that of a rectangular loop. For height ratios up to 0,2 and aspect ratios up to 3,5, the reduction does not exceed 1 dB. It is practicable, in this case, to design on the basis of H_0 and to apply the appropriate correction during final adjustment, provided the amplifier has at least 1 dB of reserve.

However, for large values of h_n , the correction becomes large, and should be taken into account at an early stage in design. A large h_n usually occurs when the loop is small, as in household installations. For example, a 5 m square loop at floor level works with h_n between 0,4 and 0,6, for seated and standing listeners respectively, using head-worn aids, while for a loop at ceiling height, for example 2,4 m, the corresponding values are 0,56 and 0,36. These values imply that to achieve at the reference point the field strength calculated for the centre of the loop, an increase in loop current, calculated from Formula (4), of 15 % to 50 % is required. It should also be noted that, when a seated listener using a head-worn aid stands up, the field strength at the telecoil changes by about 1,8 dB for the floor-level loop and about 1,7 dB for the ceiling-level loop.

10.3.4 Reference points for magnetic field strength

Because the magnetic field strength varies from point to point, it is necessary to define at least one point where the system specification should be verified. It should be noted that there can be more than one listening plane, for example if the working area includes seating at different levels, but there can be only one HLS reference plane. It is also necessary to define the permissible variation of magnetic field strength within the working area. This variation should be kept to a minimum by a suitable choice of listening height, use of multiple loops, etc. However, in practice, limitations on the siting of the loop conductor, the presence of metal in the building and the possible need, in order to avoid overspill, to use multiple or other loop configurations which produce nulls in the useful component of the magnetic field often mean that variations of the order of approximately ± 6 dB relative to the field strength at the reference point have to be accepted. In determining conformity to the specified value

nulls should be ignored, and their acceptability separately assessed. At present, this can be judged only subjectively.

In general, inadequate signal-to-noise ratio is even less acceptable than variations in field strength, so any necessary compromise should favour improvement in the former.

10.3.5 Relationship between the requirements of IEC 60118-4 and the characteristics of hearing aids and speech signals

For medical and other reasons, for example design constraints, the characteristics of hearing aids which are of interest for HLS design purposes exhibit quite wide variations. The most important of these characteristics are the "field-to-air sensitivity" which is the sound pressure level produced for a given magnetic field strength at a specified frequency, and the "field-to-air frequency response". Use of IEC 60118-4 is intended to make it unnecessary for the HLS designer to know these characteristics of hearing aids, by specifying that the magnetic field strength level 0 dB at a reference frequency of 1 kHz is 400 mA/m, and limits for its variation with frequency. However, there are indications that the designer should, in order to avoid over-simplification, be aware of the relevant characteristics of hearing aids in some depth.

The sound pressure level presented to the hearing aid user should clearly be the same, whether the signal is received by the microphone or the telecoil. However, the microphone signal varies in strength with the distance from the original source of sound, whereas the HLS signal strength is constant at a given point. It seems reasonable to adjust the field-to-air sensitivity of the hearing aid so that no great adjustment of the gain control of the aid (which normally affects the gain from both sources equally) is required when switching the aid from microphone (M) operation, where the gain control is usually set for normal conversation, to telecoil (T) operation. IEC 60118-4 implies that this is achieved if a field strength of 0,1 A/m produces the same output from the hearing aid as a sound pressure level of 70 dB (20 μ Pa).

The hearing aid user should also be presented with sound of the same spectral distribution (frequency response) whether the signal is received by the microphone or by the telecoil. The characteristics of the hearing aid amplifier and earphone are common to both modes of operation and can therefore be eliminated from consideration, except for the loading effect of the amplifier on the telecoil frequency response. It remains, therefore, to consider the frequency response characteristics of the microphone and telecoil. The frequency response of the hearing aid from microphone to earphone is known as the "air-to-air response". The characteristics of hearing aid microphones vary considerably, mainly for design reasons: all that can be said is that there is usually a falling response below 1 kHz, and one or more peaks in the 3 kHz range, before a steep fall at higher frequencies.

If the telecoil in the hearing aid had negligible losses and operated into a high-impedance load, it would produce an output voltage proportional to frequency, i.e. rising at 6 dB/octave. However, the field-to-air response can be made similar to the air-to-air response for most hearing aids if the magnetic field strength is within ± 3 dB of the value at 1 kHz over the frequency range 100 Hz to 5 kHz, in accordance with IEC 60118-4.

In practice, it is usual to adjust the current in the loop, and hence the field strength, to be -3 dB at approximately 100 Hz and 5 kHz (reference 1 kHz), the latter, in some cases, being dictated by design constraints and/or electromagnetic compatibility (EMC) considerations. Further equalization of the overall frequency response might be desirable, for example to compensate for the low frequency response of the HLS microphone(s) (which can be rising or falling, depending on the distance of the sound source from the microphone) and/or for peaks in the high frequency response.

10.3.6 Impedance of the loop

The impedance of the loop can be accurately represented by a resistance and an inductance in series, the values being given by Formulas (2) and (3) respectively. Formula (2) includes a temperature-dependent term, because external sources of heat, such as central heating pipes, or the current flowing in the loop conductor, might raise its temperature, and therefore its resistance, significantly.

The current ratings of wires suitable for loop conductors should be determined from relevant IEC or national standards. See also Clause C.2. The value of current used to determine the required current rating should be the largest current that can flow continuously, taking fault conditions into account. If no special provisions are made, this is the current required to accommodate programme peaks, i.e. at least 12 dB above the long-term average value, because under fault conditions, for example an open-circuit microphone line, this current could flow continuously. However, this criterion demands the use of a much larger conductor than that required to carry the long-term average current, and this can result in a value of loop resistance which, for some design procedures, is undesirably low. It might be preferable to provide automatic current limiting, so that currents higher than the long-term average can flow only for periods in the order of tens of seconds. In this way, programme peaks are accommodated but serious overheating of the loop conductor is prevented.

The inductance is closely determined by the dimensions of the loop; very little change can be made by altering the conductor diameter. In fact, Formula (3) can be simplified (see Clause C.3) for nearly all practical cases of single turn loops to:

$$L = 3,2 (A + B) \quad (5)$$

where L is expressed in microhenrys.

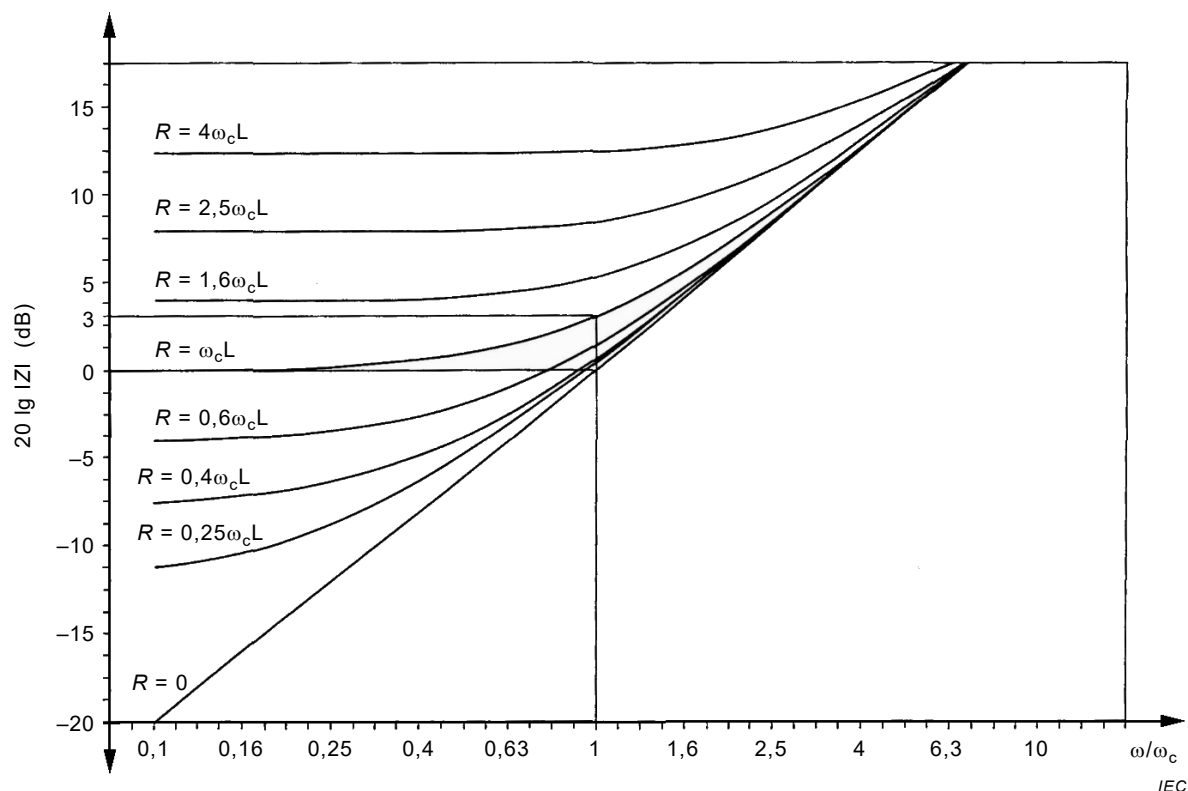
The current necessary to provide the required magnetic field strength and the impedance of the loop at the upper band-limit frequency (normally 5 kHz) determine the output capability required of the amplifier. It should be noted that the "rated output power" of the amplifier is not a very useful characteristic in this context. It is necessary for the amplifier, without producing an unacceptable amount of distortion, to be able to perform the following:

- a) supply the required current;
- b) produce enough voltage to drive $1/\sqrt{2}$ times that current through the impedance of the loop at an upper limit frequency which is lower than 5 kHz because the spectral levels of speech and music signals decline above about 1,6 kHz.

The analysis so far makes no assumptions about the value of the impedance of the loop at the upper limit frequency, relative to the value at lower frequencies. The value of the amplifier current is fixed by the size of the loop. The value of the voltage depends on the impedance, which in turn depends on the inductance and resistance. However, for practical purposes, the inductance is also fixed by the size of the loop; only the resistance is under the control of the designer, who can choose the diameter (and perhaps the material) of the loop conductor. Normally, it is kept low, so as to keep the required voltage as low as possible.

The impedance/frequency characteristics of loops with the same inductance but different values of resistance are shown in Figure 10, where the resistance values are normalized to the inductive reactance at the upper band limit frequency. It can be seen that decreasing the resistance from a normalized value of 1 to 0 reduces the value of the amplifier voltage by a factor of only $\sqrt{2}$.

NOTE A resistance or impedance is normalized to the inductive reactance at a given frequency by dividing the value of resistance or impedance by the value of the reactance at that frequency.



NOTE The impedance axis is graduated in decibels to simplify the use of the curves for determining current and voltage levels.

Figure 10 – Variation with frequency of the logarithm of the impedance of loops of constant inductance L , with the loop resistance R as parameter

10.3.7 Selection of the method of driving the loop

Although two techniques are known, termed "current drive" and "voltage drive", the common requirement is that the current in the loop conductor is independent of frequency within limits of ± 3 dB, at least over the frequency range of 100 Hz to 5 kHz.

Unless a high level of technical knowledge and skill is available, a current-drive amplifier should be selected, specially made for HLS use, including signal-presence monitoring, automatic gain control and/or compression and/or limiting, and the manufacturer's instructions should be followed concerning the selection of a suitable conductor for the loop and other matters of design. A copy of the manufacturer's instructions should be examined before the commitment to purchase is made, since their quality and intelligibility varies considerably.

10.3.8 Current-driven loop

The use of an amplifier with a high output source impedance, i.e. a "current-drive amplifier", simplifies the selection of a suitable loop conductor. The amplifier "power" requirement is minimized by using a loop conductor sufficiently thick to make the resistance negligible compared with the inductive reactance at the upper band-limit frequency. In principle, the demands on the amplifier are further reduced if the conductor is made larger still, but the practical effect is usually negligible.

Under these conditions, it is necessary to determine only that the amplifier can supply the current (in amperes) calculated from Formula (1), i.e. $I = \pi ABH_0/2D$, and that it can supply enough voltage to drive $1/\sqrt{2}$ times that current through the impedance of the loop at the upper band limit frequency.

The value of V (in V) is given by:

$$V = \sqrt{2\pi f_c L I}$$

if the loop resistance is negligible.

The high output impedance of the current-drive amplifier is obtained by applying negative feedback proportional to the output current. In some cases, this is achieved in such a way that neither of the output terminals is connected to the common return (earth). In such a case, it is essential that the loop conductor is not allowed to come into electrical contact with earthed metalwork. Manufacturers using this technique should consider the effects which would occur in the amplifier if the mains supply was inadvertently connected to the loop conductor.

Since the high output impedance of the current-drive amplifier, or the defined output impedance of the intermediate-drive amplifier, is obtained by the use of a feedback technique, it can be shown that a minimum load resistance might be necessary in order to prevent the amplifier oscillating. It is possible to build this minimum value into the amplifier, so that the output terminals can even be short-circuited without risk of oscillation. This is not always done, however, and the manufacturer's specification should be consulted to determine whether a minimum value of load resistance is stated.

Since the impedance of even large single-turn loops is quite low (a loop of 100 m perimeter has an inductive reactance of 6,3 Ω at 5 kHz), the output source impedance of the amplifier does not need to be more than a few tens of ohms in order to achieve an adequate approximation to current drive. The provision of an unnecessarily high impedance can compromise stability.

It can be shown that the operation of an amplifier with a reactive load involves increased heat dissipation in the output devices. This effect is usually negligible if only speech (and music) signals, having a high peak-to-mean ratio, are involved and there is no clipping of the signals, but results in a heat dissipation of up to 2,5 times that occurring with a resistive load, if high level sinusoidal or other continuous tone signals are present.

10.3.9 Voltage-driven loop

A loop can be driven by a constant voltage if its resistance (including any added resistive component) is not less than the inductive reactance of the loop at 5 kHz. The amplifier requires no equalization (increase in frequency response at high frequencies).

For such a loop, using Formulas (2) and (5), and taking the copper conductor temperature as 20 °C (but see Clause C.2 for the effects of temperature rise), the following formula for R (in ohms) can be derived:

$$R = 1,42 \times 10^{-7} \frac{A+B}{\pi d^2} \quad (6)$$

For a current, and therefore a magnetic field strength, at a level of -3 dB at frequency f_c with respect to its low frequency value:

$$2\pi f_c L = R$$

and if $f_c = 5$ kHz, using Formulas (5) and (6), the cross-sectional area of the loop conductor is calculated as:

$$\pi d^2/4 = 0,281 \text{ mm}^2$$

and

$$d = 0,60 \text{ mm}$$

for a loop of any dimensions (see Clause C.2). In terms of 0, a voltage-driven loop has to have a normalized resistance of 1.

NOTE It is usual to take 1 kHz as the reference frequency for HLS measurements and specifications. However, an unequalized HLS behaves as a first-order low-pass filter, and if the upper (–3 dB) band limit is 5 kHz, the response at 1 kHz is –0,17 dB relative to the value at a very low frequency. This discrepancy, or any similar discrepancy in the response of an equalized system, is usually negligible, but can cause confusion if the designer does not bear it in mind. If the upper band limit frequency is lower than 5 kHz, it can be necessary to take the resulting larger discrepancy into account.

The value of d calculated above is the diameter of conductor that produces a band limit frequency of 5 kHz; a thicker conductor produces a smaller bandwidth, and a thinner conductor allows a greater bandwidth. It should be noted that this result is independent of the size of the loop.

For a very small HLS, such as for a single living room or small committee room, a single turn loop might have an inconveniently low impedance unless a very thin and fragile conductor is used. It is possible to include a fixed resistance in series with the loop. Alternatively, a multi-turn loop can be used. The formulas for the characteristics of multi-turn loops are given in 0. Because, relative to a single turn loop, the inductance of an n -turn loop is increased approximately n^2 times, while the resistance is increased only n times, very thin (high resistance) conductors are necessary for multi-turn voltage-driven unequalized loops in order to keep the normalized resistance equal to 1 (see the Note to 0).

In the case of a very small multi-turn loop, such as a neck loop or a ticket office system (see Clause 9 and Annex B), the use of a series resistor, of adequate power dissipation, might be the optimum technique.

10.3.10 Voltage-driven loop with high-level equalization

If the loop dimensions are too large, or the chosen conductor is of too low resistance, for the loop to be voltage-driven without equalization, it is possible to provide this by connecting a network, consisting of a capacitor and a resistor in parallel, in series with the loop (see Figure 11). Careful design is necessary in order to achieve correct results. The technique could be of use if it is necessary or convenient to use an amplifier designed for "voltage line" (e.g. 100 V or 70 V) service, perhaps because other amplifiers of the same type are used for sound reinforcement in the same building, and in this case, a loop impedance higher than the optimum for other techniques is required. This is one of the cases where it can be advantageous to use a loop of more than one turn.

Another reason for considering this technique is that the equalization can be applied without making modifications to the amplifier or providing more than a minimum of supplementary equipment; the components can be incorporated in a terminal box where the amplifier output lead meets the loop conductor. Amplifiers for 25 V or 50 V line operation can be connected to loops of the appropriate impedance directly: those for 70 V or 100 V line operation can need a transformer unless the loop perimeter or the number of turns is large.

For a loop of n turns, the design formulas are converted as follows. The value of the current (in amperes) is given by:

$$I = \frac{\pi ABH_0}{2nD} \quad (7)$$

The value of the resistance (in ohms) is given by:

$$R = \frac{8n\rho_0(1+a\theta)(A+B)}{\pi d^2} \quad (8)$$

The value of the inductance (in microhenrys) is given by:

$$L = 3,2n^2 (A + B) \quad (9)$$

Compared with a single turn, the value of the current needed is reduced n times, but the inductive reactance at the upper band limit is increased n^2 times, so the value of the amplifier voltage output needed is increased, by a factor that depends on the normalized resistance of the n -turn loop. For example, if the single turn has a normalized resistance of 1, an n -turn loop of the same conductor has a normalized resistance of $1/n$, and the normalized impedance at the upper band limit is $\sqrt{1+1/n^2}$, and is predominantly inductive. It can be seen that very little is to be gained, in terms of minimizing amplifier "power" (i.e. voltage requirement times the current requirement), by using more than three turns which give a normalized impedance of 1,054. The actual impedance continues to increase as n^2 .

NOTE 1 Alternatively, since the n -turn loop requires only $1/n$ times the current for the single turn, the conductor cross-sectional area could be reduced in proportion. This results in an n -turn loop with a normalized resistance of 1, which could be voltage driven without equalization, but the conductor has to be very thin (e.g. a maximum area of 0,098 mm² for a three-turn loop). It is difficult to install such thin conductors without damage, and to protect them adequately so that they are not broken by movement of the building structure due to temperature and humidity changes. However, they can be used in neck loops.

NOTE 2 Because the equalizer network effectively presents the amplifier with a mainly resistive load, the use of this technique does not involve any extra heat dissipation in the amplifier, as is required in other cases.

If equalization is employed, it should be exploited to give the maximum practical advantage, in reducing the amplifier "power" requirement. It can be shown that the maximum possible reduction is by a factor of 2, which implies zero loop resistance.

It is shown in C.4.5 that, for a given shape of frequency characteristic and value of upper band limit frequency, there is a unique solution for the values of the components R_1 , R_2 and C shown in Figure 10, in terms of the inductance L (in henrys), which itself is practically fixed by the loop dimensions. The design formulas, for a practicable case, giving a nearly flat frequency response, are as follows.

The value of R_1 (in ohms) is given by: $R_1 = \frac{2\pi f_c L}{2,652}$

The value of R_2 (in ohms) is given by: $R_2 = \frac{2\pi f_c L}{3,751}$

The value of C (in farads) is given by: $C = \frac{4,121}{4\pi^2 f_c^2 L}$

Thus, the normalized resistance of the loop is $1/3,751$, i.e. 0,267, and the normalized impedance is 1,035, which is very close to the theoretical minimum. While R_1 and C are discrete components, R_2 is the resistance of the loop, and the conductor size should be chosen to achieve this value of resistance (while being of adequate current rating); a small discrete padding resistor can be necessary. It should be noted that the discrete resistors can dissipate considerable power, particularly under fault conditions giving a constant high loop current. If R_2 is too large, a padding inductor can be used, or a higher value of f_c accepted, so that the above formula for R_2 is satisfied.

The fact that a constant voltage applied to the input of the equalizer (see Figure 11) produces a nearly constant current in the loop at any frequency, falling by 3 dB at the upper band limit