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Induction Loop Listening System Designed for a Classroom[a]

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Abstract—The principles of designing an induction loop listening system are discussed. Step-by-step procedures for building an induction loop are presented. The loop described was installed in a medium-size classroom and listening tests were performed comparing the loop and loudspeakers. Two groups of hearing impaired listeners were used. One group of listeners wore hearing aids while the other group did not. Results indicated that for both groups, speech perception was enhanced with the loop system.

INTRODUCTION

Spoken communication among people involves transmission of acoustic waves from a source through an environment to a receiver (listener). A poor acoustical environment caused by noise, excessive reverberation, and distance between talker and listener, creates unfavorable listening conditions for all listeners. However, it poses especially serious problems for the hearing impaired community (1, 2). Many elderly listeners with only the mild hearing losses typical of their age also experience increased difficulty in understanding speech in noise and in reverberation (3, 4).

To assure that the speech reaching a listener contains the most important cues necessary for speech recognition, a high speech-to-noise ratio (S/N) and short reverberation time are required. In order for the hearing impaired person to receive speech clearly, the speech should be 10 dB to 20 dB higher than the background noise (5, 6). Room reverberation also contributes to a low S/N; sound reflecting from one surface to another increases the level of the "background noise". This causes auditory confusion for the hearing impaired person and often results in reduced speech perception.

Short reverberation time and high S/N are imperative requirements for the acoustical design of places used by hearing impaired and elderly listeners, but in many cases existing acoustics cannot be easily improved and additional electroacoustical systems are required. Since open-field public address (PA) systems are of little benefit to the hearing impaired listener (7), the dedicated listening systems (which provide better microphone placement than may be obtained under the constraints of the conventional hearing aid) have to be considered. The Architectural and Transportation Barriers Compliance Board (ATBCB) issued a ruling effective January 6 1981 establishing guidelines and requirements for accessibility and usability of federal and federally funded buildings and facilities for physically handicapped persons (46 Federal Register 4270).

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The final ATBCB rule stated, in part: "Assembly areas must be provided with a listening system to assist no fewer than two persons with severe hearing loss." The rule states that acceptable types of listening systems include, but are not limited to, audio loops and radio frequency systems. A building designed, constructed, altered, or leased after the effective date of an accessibility standard issued under the Architectural Barriers Act (1968) must comply with the standard.

There are four basic types of listening systems: (i) hard-wired systems, (ii) induction loop systems, (iii) radio frequency broadcasting systems, and (iv) infrared-light transmission systems. This paper discusses design principles, installation, and performance evaluation of an actual induction loop system installed in a medium-size classroom. This design can be replicated easily in places such as auditoriums, small churches and conference rooms requiring permanent use of a reliable listening system. The design and construction of an induction loop system is simple and inexpensive. Basic advantages and limitations of such a system are given in Table 1.

SYSTEM DESIGN CALCULATIONS

Induction Loop Principle

The induction loop system consists of a multiturn wire loop (transmitting loop) encircling the area to be served, with both loop ends connected to the output of an audio amplifier into which the program material is delivered. The amplifier's output creates a changing electric current passing through the loop, and that, in turn, creates a changing magnetic field in the area within the loop. The changes in that magnetic field's strength carry, in analog form, the program material fed into the audio amplifier.

If someone within the circle of the transmitting loop is carrying a small pickup loop, the changing magnetic field concentrated in that area will induce a similarly changing electric current flow in the small loop. If the small loop is connected to the input of a receiving amplifier (or if the small loop is the teleloop of a hearing aid with a "T" switch) the electrical current will produce an acoustic signal when it passes through an electroacoustic transducer located at the listener's ear.

An induction loop system can be used either as a permanent installation or as a portable facility for both individual and group listening. Another important feature of this system is that its amplifier can be used (without any change in the loop installation) as part of a public address system when connected to a loudspeaker.

The dimensions of the loop depend upon the shape and area of the room to be served.

Induction loop systems can work as either direct audio-frequency, or high-frequency, transmission systems. In the latter case, either amplitude modulation (AM) or frequency modulation (FM) can be

TABLE 1
Advantages and limitations of induction loop listening systems

ADVANTAGES
Low cost of hardware
Low operational cost, especially when used for individuals who wear hearing aids*
Ease of use
Simplicity of maintenance
Inconspicious apparatus and operation**
Low power consumption by receivers (hearing aids*) which result in long-lasting batteries
LIMITATIONS
Relatively low signal-to-noise ratio
Vulnerability to magnetic interferences (electrical wiring, electric motors, fluorescent lamps, and transformers)
Limited frequency response
Directional character of the magnetic field and the possibility of signal strength variation within the loop area
Technical difficulties when installed in large areas, and **limited portability**
Single-channel limitation* **
High loop-power requirement

*This requires hearing aids equipped with inductive pick-up coils intended for use with telephones, and activated by a so-called "T" (telephone) switch.

**This refers to audio frequency induction loops used in combination with hearing aid receivers.

***However, an induction loop used as a radio frequency (RF) inductive antenna can be utilized for a single- or multi-channel system.

Journal of Rehabilitation Research and Development Vol. 23 No. 1 1986

employed to carry the low frequency audio signals. High frequency induction loop systems, due to their multichannel capability, are primarily used in simultaneous translation systems. Audio frequency induction loop systems are usually employed in schools for hearing impaired children, as attachments to home radio and/or television receivers, and in such public places as theaters, cinemas, auditoriums, churches, synagogues, and meeting halls, for the benefit of anyone experiencing difficulties in sound perception. A personal hearing aid used as an audio loop receiver enables the wearer to take advantage of an audio loop signal transmission whenever such loops are available, assuming that a proper magnetic field strength is provided.

Geometrical Considerations of the Site

The classroom chosen for the installation of the induction loop system to be described here is rectangular in shape. All electrical wiring and outlets, and windows, are on the outer (longer) wall. The room has two doors near its corners in the wall opposite the windows. The volume (V) of the room is 91.2 m^3 (7.6 × 5.0 × 2.4 m). The floor of the room is fully carpeted, the ceiling is tiled with acoustical panels, and there are three fluorescent light arrays with axes perpendicular to the windows. Room wall surface construction consists of painted cinder blocks. Room reverberation time was 0.35 seconds (average value of octave bands of noise centered at 500 Hz, 1000 Hz, and 2000 Hz) measured with the signal source located on the room axis at 3 m from the room center (microphone location) and at about 1 m from the adjacent wall. The average level of the ambient noise in the classroom was 62 dB (46 dB A weighting, 32 dB Leq) with occasional peaks reaching 72 dB.

The basic design consideration for induction loop construction is the size and location of the "specified listening area." That area is not necessarily the entire geometric area containing the induction loop; it is usually defined as the area of the room where the intensity of the magnetic field produced by the loop at 500 Hz does not deviate by more than 3 dB from a value measured at the central listening point. These data refer to the vertical component (H_v) of the magnetic field, since the horizontal component (H_h) is usually ignored in the loop design. This is because: (i) the vertical field strength predominates over most of the loop area, (ii) the telecoils in hearing aids are typically positioned to be most sensitive to the vertical field, and (iii) rotation of the hearing aid about the vertical axis (as in turning the head) results in no change in the strength of the pick-up from the vertical component, whereas the pick-up from the field's horizontal component can change from maximum to zero with such rotation.

To obtain the largest possible listening area, the loop was located next to room boundaries encircling the floor area S = 38.15 m^2. When routing a loop, it is important to avoid any electrical wires in the proximity of the loop, especially where placement would put the loop and existing wires parallel to each other. Another basic rule in routing a loop is to maintain as large a distance as possible between any steel elements of the building's structure and the loop. In the installation described here, it was necessary to avoid electrical wiring located in the upper part of the room, and metal structure supporting the ceiling. The solution was to place the loop at the floor level (under the carpet) since it was not prohibited by required listening height (h), i.e. the distance between the loop plane and the listener plane.

Listening height has an important effect upon the uniformity of the magnetic field in the listening area. The greater the value of the coefficient C relating listening height (h) and the size of the listening area (S)

$$C = \frac{h}{(S/2)^{1/2}} \qquad [1]$$

the less the variability of magnetic field strength inside the loop in the listening plane. According to Philbrick (8) the value of the coefficient C should be between 0.15 and 0.20 to provide the best compromise between the area of coverage and the acceptable range of variation in magnetic field strength, giving a maximum 4 dB range of vertical field strength within more than 95 percent of the loop area. In rectangular loops, the minimum listening height also depends slightly on a side ratio. For a loop with a side ratio of 1:1.6, which is the side ratio of the designed loop, the value of coefficient C should be greater than 0.2 to assure that the maximum range of variation in magnetic field is less than 4 dB. Thus, according to formula [1], the minimum listening height value of the designed loop system should fullfill the condition

$$h_{min} > C\,(S/2)^{1/2} \qquad [2]$$

and

$$h_{min} > 0.2\,(38.15/2)^{1/2} = 0.87 \text{ m} \qquad [3]$$

Since the above h value secures the proper listening conditions for both sitting adults and walking/standing children, the loop placement at the floor level was ultimately accepted.

Magnetic Field Intensity

Once the size and location of the loop have been decided, the required electric current flowing in the loop has to be calculated. The required value of the current is determined by the magnetic field intensity needed to produce a signal 30 dB to 40 dB higher than the level of the ambient noise (5). The ambient noise is produced by electromagnetic fields other than the loop. The required value of current is also partly determined by loop geometry.

The international standards for the magnetic field intensity produced by audio induction loop systems call for the level -20 dB re 1 A/m* at 1000 Hz with an input signal at a level equal to the long-time average value of the speech signal applied to the input of the system (9, 10, 11). This field intensity roughly corresponds to the volume control setting needed on hearing aids for acoustical reception in typical environments. In other words, when a person listening through a hearing aid switches from the "T" (telecoil) to "M" (microphone) mode of reception, the sound of someone speaking normally should be approximately as loud as the sound produced by electromagnetic transmission from the loop.

On the other hand, the intensity of the magnetic field should not be so high that it could overload a hearing aid or a receiving amplifier. According to IEC recommendations, maximum magnetic field intensity should not exceed -8 dB re 1 A/m at 1000 Hz (9, 10). This maximum value is derived using the premise that the ratio of the maximum short-time average level of a speech signal (approx. 0.125 s) to the long-time average level is approximately 12 dB (10).

The magnetic ambient noise in the classroom was measured using the Flux Probe Eagle Model DL-100. The vertical component of the field was much stronger than any component in the horizontal plane, and varied between 0.001 and 0.002 A/m throughout the room. When the frequency component of 60 Hz was filtered out, the magnetic noise level dropped below 0.0003 and 0.0006 A/m with lights and air conditioner unit turned off and on, respectively. These results indicate that, for a nominal magnetic field intensity of 0.1 A/m and with the 60-Hz noise component filtered out, the signal-to-noise ratio for electromagnetic transmission exceeds 45-50 dB—which assures acceptable listening conditions.

*A/m is an abbreviation for "ampere-turns per meter," a measure of the combined effect of coil turns, current flow, and distance, in calculating field strength.

Loop Current Intensity

Biot and Savart, two French physicists, formulated the law for magnetic field intensity (dH_V) at a distance (r) from a segment of a conducting wire (ds) carrying current of intensity (I) with α the angle between (s) and (r):

$$dH_V = \frac{I \sin \alpha}{r^2} ds \qquad [4]$$

For a rectangular loop and an observation point located in the listening plane, formula [4] leads to the equation

$$H_V = \frac{4 \times I \times h}{\pi(4h^2 + a^2 + b^2)^{1/2}} \left(\frac{1}{(4h^2 + b^2)^{1/2}} + \frac{1}{(4h^2 + a^2)^{1/2}} \right) \qquad [5]$$

where a and b are dimensions of the sides of the loop, h is a listening height, and I is a current intensity. Assuming that $H_V = 0.1$ A/m, and that h changes between 0.9 m and 1.8 m, which covers various listening heights including a standing adult, the required nominal value of a loop current in the system is I = 2.5 A. The short-term maximum current requirements call for the value

$$I_{max} = 4 \times I = 10\,A \qquad [6]$$

since the natural peaks of speech can exceed the average value by some 12 dB.

Loop Design

The required total cross-sectional area (CSA) of the loop conductors can be calculated from the formula

$$I_{max} = CSA \times id \qquad [7]$$

where id = 2 A/mm² is an assumed maximum current density in the conductor. Thus,

$$CSA = \frac{I_{max}}{id} = 5\,mm^2 \qquad [8]$$

A loop wire size and number of loop turns can be consecutively selected for the wire that will conduct the required current intensity safely and will provide a required resistance value (R) matching that of the amplifier. Since

$$R = \zeta np/F \qquad [9]$$

and

$$CSA = nF \qquad [10]$$

where CSA is the total cross-sectional area of the loop conductors, F is the cross-sectional area of a single loop wire, n is the number of loop turns, p is loop perimeter, and ζ is resistivity of the loop wire (ζ = 0.025 for metal compound used typically in elec-

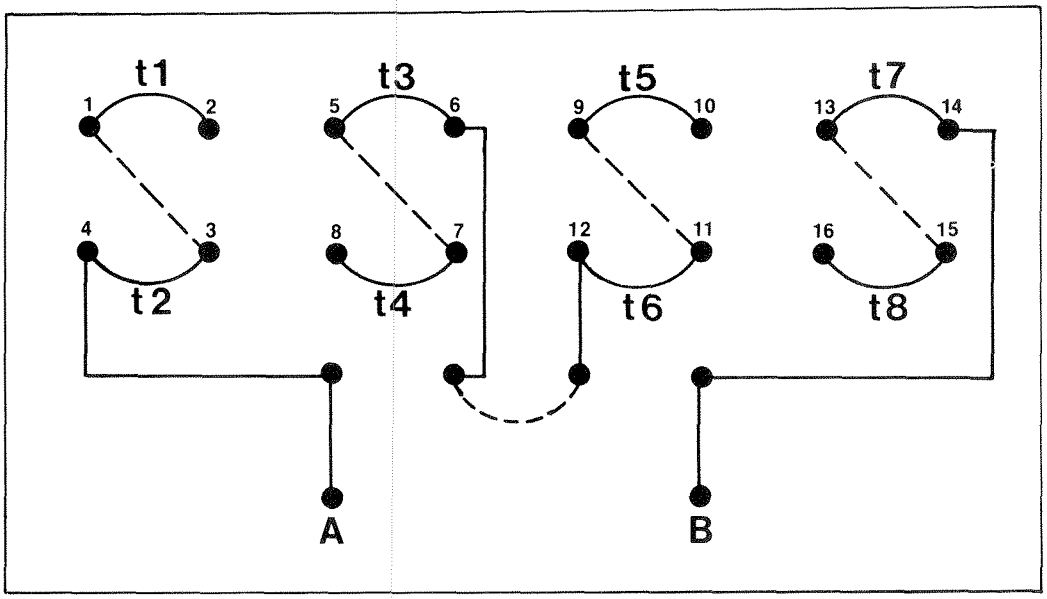

FIGURE 1
Schematic of loop wiring. Symbols t1-t8 indicate loop turn number, and numbers from 1 to 16 indicate the beginning (odd number) and the end (even number) of a turn.

troacoustical wiring), then

$$n = (CSA\ R/\xi\ p)^{1/2} \qquad [11]$$

For the values determined above, formula [11] gives a value for n of 7.3, leading to eight as the number of loop turns required. The cross-sectional area of the individual wires should exceed 0.625 mm^2.

To comply with the above requirements, we have chosen Beldon 9A22016 flat cable consisting of 16 wires, each of 0.76 mm diameter (22 gauge). By using two wires in parallel per turn (16 wires connected in 8 pairs) we have met our cross-sectional area requirements. The schematic of the wire connections is given in Figure 1, where solid lines indicate permanent connections and broken lines indicate the connections to be made with plugs and sockets. The arrangement allows for loop configurations to match other resistance values or/and other magnetic field requirements, if needed.

Frequency Response

The loop circuit has both resistive and inductive character (RL circuit). The loop impedance value increases with the signal frequency, resulting in a lowering of the current intensity and of the magnetic field intensity at higher frequencies. The upper limiting frequency f_{UL} (3 dB signal loss) for an RL circuit formed by the loop can be calculated from the formula

$$f_{UL} = R/2\pi L \qquad [12]$$

where L is loop inductance. In the case of the rectangular loop, inductance L can be calculated from the formula given by Dalsgaard (12)

$$L = 0.092\,(S)^{1/2}\,n^2\,[6 + \log(S/F)]\,10^{-6} \qquad [13]$$

where F is wire cross-sectional area and S is the area encircled by the loop. The inductance value for the loop in question is 275 μH. Thus, according to equation [12], upper limiting frequency f_{UL} will be in the range between 4500 Hz and 5000 Hz.

Power Requirements

For a loop with resistance (R), the output power (P) supplied by the power amplifier may be determined by the expression

$$P = R\,I^2 \qquad [14]$$

Assuming that nominal current intensity does not exceed 2.5 A and that loop resistance equals 8 ohms, the nominal power required from the power amplifier would be 50 W. However, to secure undistorted peak signal intensities which require up to 10 A of current, the short-term power rating should allow 800 W.

PERFORMANCE TESTING

System Arrangement and Adjustment

The block diagram of the induction loop installation is presented in Figure 2. A McIntosh 40 Power Amplifier, rated at 200 W/8 ohms, was used to provide power to the loop. Initial tests with various hearing aids (Phonic Ear, Siemens, and Widex) confirmed the satisfactory power capacity of the loop.

The frequency response of the loop system (Figure

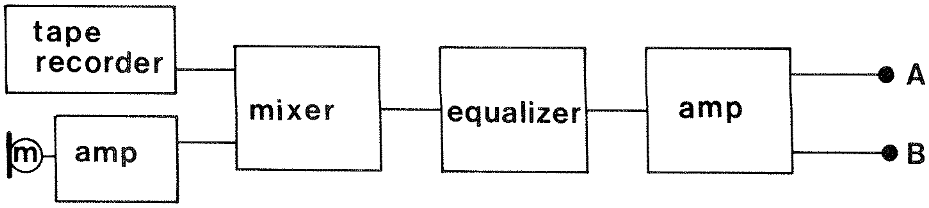

FIGURE 2
Block diagram of induction loop installation (m — microphone, amp — amplifier). A and B are loop inputs as shown in Figure 1.

3) is adequate for speech signal transmission. However, in addition to its basic applications, the loop was intended for use in various research projects. A Soundcraftsman One-third-octave-band Equalizer was then added to the loop circuit, to extend the frequency response. The equalizer was adjusted for a constant voltage at the output of the field-strength probe (Eagle DL-100) which simulated a hearing aid working in telephone mode. The resulting frequency response in the center of the room is shown in Figure 3. Spatial variability of the magnetic field intensity (H_V) within 0.5 m distance of the side walls was 1.5 dB, 4.2 dB, and 3.3 dB for 100 Hz, 1000 Hz, and pink noise signal, respectively.

Listening Tests

To test the performance of the loop, a comparative speech perception test was conducted with the induction loop system and PA system in the classroom. The PA system employed a power amplifier identical to the one used with the induction loop. Two identical loudspeakers located 0.5 m apart on the shorter wall of the classroom were used.

The speech test was the Modified Rhyme Test (MRT) (13). This is a forced-choice six-alternative test in which the test items are initial or final consonants in monosyllabic words embedded in a carrier phrase. Each list consists of 50 test items. The MRT was played on a Revox A700 tape recorder connected to the inputs of both the induction-loop and the PA systems. Subjects had to respond to MRT tasks presented either through the PA system alone or through PA and induction loop systems working simultaneously. These two conditions simulated the typical situations in an auditorium. The intensity of speech reproduced by the PA system was set at 66 dB (A) level, when measured 1 m in front of the loudspeakers. This level was kept constant throughout the experiment.

There were two modes of presenting the MRT: without and with a babble of 12 voices added as background noise. The level of the babble was set at 58 dB (A) when measured at the same point as the speech level. The babble was reproduced by a third loudspeaker placed midway between the loudspeakers reproducing MRT.

The subjects were seated in front of the loudspeakers at a distance of 3 m. The speech-to-noise ratio (S/N) at this distance was +20 dB and +8 dB, without and with babble, respectively. Each condition was tested with two MRT lists (a total of 100 words).

Two groups of subjects were tested: (i) hearing impaired subjects with mild-to-moderate hearing loss and not using hearing aids, and (ii) hearing aid users with moderate hearing loss. The average losses at 250, 500, 1000, 2000, 4000, and 8000 Hz for the first group were 22.0, 16.5, 22.0, 29.5, 55.0, and 62.5 dB for the right ear and 28.5, 19.5, 20.5, 36.5, 58.0, and 65.0 dB for the left ear, respectively. The average hearing losses at the same frequencies for the second group were 28.5, 35.0, 46.0, 55.5, 61.0, and 66.5 dB for the right ear and 35.0, 37.0, 48.5, 55.5, 65.0, and 65.0 dB for the left ear, respectively. There were 10 subjects in each group.

The hearing aid users had binaural hearing losses but they were each using only one hearing aid. They were tested with their own hearing aids which had been fitted by audiologists. The hearing aids were different makes, but all of them had a telecoil (T) switch. The subjects used the microphone input for listening to the PA system and the telecoil input to listen to the induction loop signal. In each mode they were allowed to set the gain for comfortable listening.

The results of the listening tests indicated that the differences between the performances of the groups were small and nonsignificant. There were, however, significant differences for both groups in discrimination scores obtained without and with the induction loop system. The mean average scores (both groups together) for the PA system alone were 87 percent and 81 percent without and with babble, respectively. The analogous scores for the PA system working together with the induction loop system were 93 percent and 91 percent without and with babble, respectively. Thus, the improvement

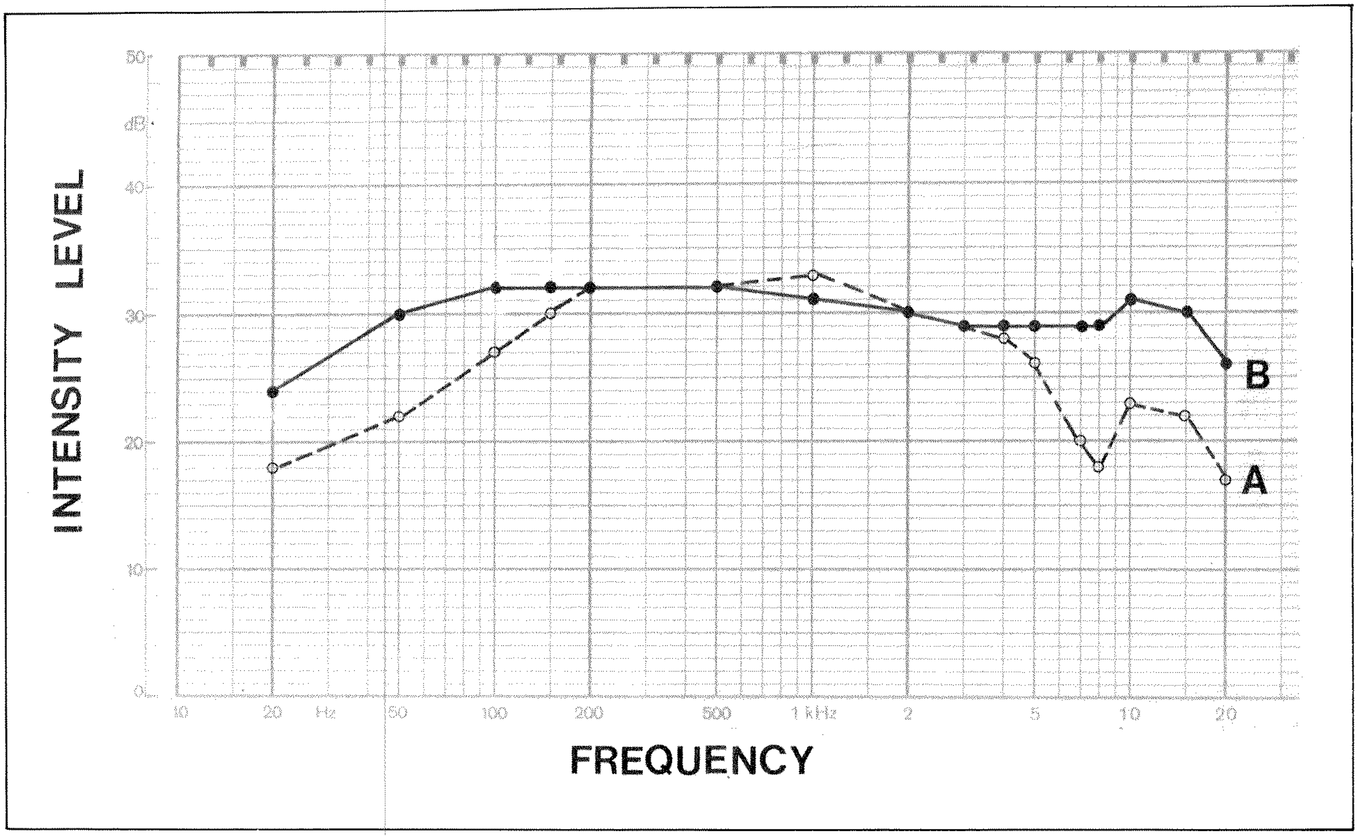

FIGURE 3 — Frequency response of the induction loop without (A) and with (B) equalization.

provided by the induction loop was 6 percent and 10 percent without and with babble, respectively. Both these values were significant at 0.05 level.

The data listed above show that a properly designed induction-loop system can provide high quality signal transmission and is a satisfactory solution to hearing impaired listeners' needs under conditions such as those described. Should the tested S/N be lower and the reverberation time in the classroom be longer, we would expect the achieved improvements to be even greater ■

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