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Achieving and estimation of acoustical or speech privacy in open plant offices via sound masking systems

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***Abstract**: One of the problems in open plant offices is the existence of unwanted sounds, usually like speech or conversations present in the workplace of each staff member, which are caused by the surrounding working people in the open office. This usually leads to the annoyance and distraction of the working people in the open offices. There are a number of methods and means to combat from these unpleasant sounds disturbing people in their jobs and one of them is the popular method of sound masking. Generally the sound-masking methods and corresponding sound masking systems are used to minimize any undesired sounds or noises. Usually in open plant offices the annoyance and distraction sound sources are from human speech and people conversations around each of the working places. Therefore, it is logic and preferable to estimate the effectiveness of used sound masking methods and systems only from the values of measured speech privacy. The goal of this article is to achieve of speech privacy applying sound masking system as the mean of suppressing the incoming unwanted speeches to each working place in open plant office. The experiments of testing the achieved speech privacy applying appropriate sound masking system are carried out in three chosen open office premises: the open plant office, private office and conference room. The effectiveness estimation of the achieved speech privacy is made in two ways: calculating Speech Transmission Index – STI and Privacy Index – PI. The results from the tests shows that the achieved speech privacy with the sound masking system can be estimated correctly from the measured values of STI and PI obtained in all of the examined premises in an open office and this estimations correspond to the carried out similar subjective estimations of speech privacy during the tests.*

***Keywords**: speech privacy, sound masking, open offices, speech transmission index - STI, privacy index - PI*

I. Introduction

Sound masking systems can be used to reduce impact of any unwanted sounds on each working place in the open plant offices [1]. Typically, in open offices with multiple staff, sources of unwanted sounds are usually speech or conversations present in the workplace of each staff member and caused by the surrounding working people in the open office. Therefore, it can be considered the sound masking tasks in the open plant offices as acoustical or more specifically speech privacy tasks.

Generally speech privacy is defined as methods and means leading to inability of an unintentional listener to understand another person's the conversation [2]. There are a lot of methods and means to achieve acoustical or speech privacy [3].

The goal of this article is to achieve the effective speech privacy applying sound masking system as the mean of suppression the incoming unwanted speeches to each working place in open plant office.

The subject of tests of achieved speech privacy using sound masking systems are three different premises in typical office building: the open plant office, private office and conference room.

Usually the estimation of the level of achieving speech privacy can be subjective or objective. Here in this article are applied the objective means to determine and estimation of the level of achieving speech privacy and they are compared with the subjective estimations of speech privacy carried out simultaneously with the objective measurements of speech privacy during the tests.

To realize in comparative form the objective estimation of achieved in the tests of speech privacy for each of the chosen three open office premises, it is proposed to apply two well knowns and wide spread standards ANSI S3.5 [4] and ASTM E1130 [5]. In these standards the speech privacy is estimated as Speech Transmission Index – STI [6] and Privacy Index – PI [7], respectively. Both of them are using Articulation Index - AI [8] to yields the speech privacy but with different algorithms..

II. The basic principles of Speech Privacy definition and estimations

The speech privacy is a standardized metrics to determine objectively or quantitatively the amount of speech intelligibility. Of course, speech privacy or speech intelligibility can be also treated as subjective term and estimated from subjective test carried out, asking each person in the tested open plant offices, for their personally perception of speech privacy. From the human point of view and from different situations in open plant offices speech privacy can be separated and described in the following types, usually related with the degrees of privacy [9]:
- **Secret privacy** – when the people conversations cannot be intelligible to others even when deliberate attempts to listen are made using sensing devices;
- **Confidential Privacy** – when the people conversations are unintelligible to casual listeners, which mean that the conversations may, or may not, be audible;
- **Normal Privacy** - two people have normal privacy from each other, when their conversations do not distract each other and their speech will be audible and partially intelligible;
- **Transitional Privacy** - two people have transitional privacy from each other, when their conversations may distract each other occasionally and their speech will be audible and partially intelligible;
- **No Privacy** - two people have no Privacy from each other, when their conversations are clearly intelligible and completely distracting.

Depending of the mentioned above types of speech privacy it is necessary in the objective and subjective estimations of speech privacy to consider also the corresponding distance at which acceptable privacy is achieved. The term describing distance of acceptable privacy is called **Radius of Distraction**, which means - people can be distracted by the conversation of the person at the center of the circle [10].

Independently from the mentioned above types of speech privacy, it is possible to present in general form the equation, which define the speech sound level SL_{WP} in the working place of each person in open plant office. This speech sound level SL_{WP} can be describe as following combination as summary sound level SL_{SP} from existing conversations, decreasing with the sound level SL_{AT} of personal threshold of attention and decreasing with the sound level SL_{SM} of sound masking, if the sound masking system is used to achieve appropriate speech privacy or intelligibility:

$$SL_{WP} = SL_{SP} - SL_{AT} - SL_{SM} \quad (1)$$

From equation (1) is clear, that for the given sound levels SL_{SP} of existing conversations and sound level SL_{AT} of personal threshold of attention the only way to achieve effective speech privacy, i.e. to decrease the unwanted speech in some working place in open plant office, is to increasing the sound level SL_{SM} of the used sound masking system. This conclusion should be used in observation of some obvious and practically important constraints and limitations like these:
- an important limitation on the application of sound masking is, that the masking sound level SL_{SM} must not be so loud, that to be perceived as an annoyance;
- similarly if the adjacent working persons in the open plant office are well placed, i.e. acoustically at a sufficient distance each other, then sound masking may not be needed.

The above mentioned constraints are the basis in this article to propose to apply sound masking as a mean of achieving the appropriate speech privacy in open plant offices. It is proposed also to apply and evaluate the effectiveness of speech privacy with suitable methods. As the concrete methods for effectiveness estimation of the achieved speech privacy are chosen the Speech Transmission Index – STI and Privacy Index – PI. The results from measurements of these indexes are subjects of comparison in the experiments, carried out in this article. Both the Speech Transmission Index – STI and Privacy Index – PI are based on the Articulation Index – AI and are wide used as popular means of speech privacy estimation.

Articulation Index (AI) is defined [5, 8] as a measure of speech intelligibility estimating its spectrum, the sound attenuation spectrum between talker and listener, and the background or masking spectrum at the listener, using the following equations:

$$AI = \sum_{i=200}^{5000} SNR_i * WI_i , \quad (2)$$

where

SNR_i is the signal-to-noise ratio in each 1⁄3 octave band from 200 to 5000 Hz:

$$SNR_i = VS_i - TL_i - MS_i ; \quad (3)$$

VS_i - the speech spectrum, specified by ASTM [5];

TL_i - the sound attenuation spectrum between talker and listener;

MS_i - either the sound masking or background spectrum;

WI_i - the intelligibility weighting factor.

The values of calculated Articulation Index (AI) are between 0 and 1, if the following constraints are applied:

for $SNR_i < 0$ to set $SNR_i = 0$; (4)

for $SNR_i > 30$ to set $SNR_i = 30$. (5)

The above constraints define, that the speech intelligibility in a frequency band cannot be less than zero, nor greater than full speech understanding.

The Speech Transmission Index – STI, defined and detailed describe in ANSI S3.5 standard [4], is a rating of Speech Intelligibility Index (SII) [6]. For the calculations and measurements of Speech Transmission Index (STI) is necessary to use of a special sound source, so that with proper instrumentation, the rating can be calculated immediately, unlike the other ratings such as PI that require several separate measurements. The Speech Transmission Index (STI) and its modification Rapid Speech Transmission Index (RASTI) can be calculated from the impulse response using the modulation transfer function (MTF), which is defined as the magnitude of the Fourier transform of the squared impulse response divided by the total energy in the impulse response. Therefore in this article it is described briefly, with the following equations, only for its application in the experiments of speech privacy estimation of the achieved speech privacy in open plant offices where is applied a sound masking system:

$$m(F) = \frac{m_{per}}{m_{emi}}, \tag{6}$$

where

$m(F)$ is the Modulation Transfer Function (MTF);

m_{per} - the perceived sound signal;

m_{emi} - the emited sound signal.

After the calculation of Modulation Transfer Function (MTF), the apparent signal-to-noise ratio (SNR) in each band, $aSNR_i$ is computed as:

$$aSNR_i = 10\log_{10}\left(\frac{m(F)}{1-m(F)}\right) \tag{7}$$

Then the calculated apparent signal-to-noise ratio $aSNR_i$ is clipped to $\pm 15dB$:

$$TI_i = \frac{aSNR_i + 15}{30} \tag{8}$$

The desired value of Speech Transmission Index (STI) is determined from TI_i as:

$$STI = \sum_{1}^{7} \alpha_i TI_i - \sum_{1}^{6} \beta_i \sqrt{TI_i * TI_{i+1}}, \tag{9}$$

where

α_i represent the octave band weighting factors;

β_i - the redundancy correction factors.

The Privacy Index – PI is defined and detailed describe in ASTM E1130 standard [5, 7], therefore in this article it is described briefly, with the following equations, only for its application in the experiments of speech privacy estimation of the achieved speech privacy in open plant offices where is applied a sound masking system:

$$PI = 100*(1-AI) \tag{10}$$

$$PI = 100*(1.06-0.97*SII), \tag{11}$$

where SII is the calculated Speech Intelligibility Index [6].

III. Experimental results from tests of achieved speech privacy applying appropriate sound masking system

The initial definitions and conditions used in the tests carried out in the experiments of testing the achieved speech privacy applying appropriate sound masking system are the following:

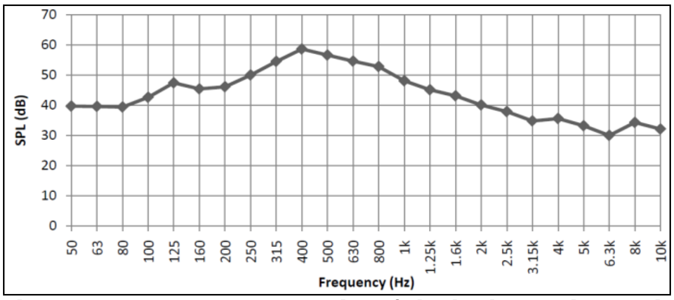
- definition and measurements (in 60 seconds) of the appropriate speech levels of talker (or talkers in a conversation) in open plant office, presented on Table I;

Table I Speech levels definition of talker (or talkers in a conversation) in open plant office, measured for 60 seconds

Voice level	SPL dB(A)
Low	53-55
Normal	60-62
Medium Loud	65-68
Loud	>70

- definition and calculation of average speech spectrum of talker (or talkers in a conversation), shown on Fig.1:

Figure 1 Defined and calculated average speech spectrum of talker (or talkers in a conversation)



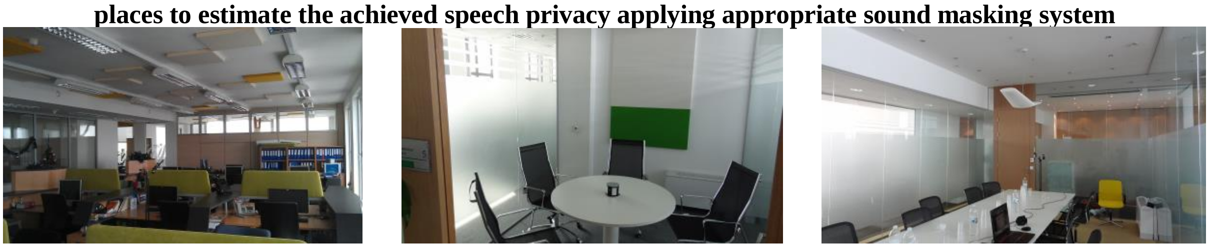
- definition (Table II) and measurements (in 60 seconds) of the background noise level for the chosen three different premises in typical office building: the open plant office (Fig.2), private office or cabinet/closed office (Fig.3) and conference room (Fig.4).

Table II Definition and measurements (in 60 seconds) of the background noise level for the chosen three different premises in typical office building: the open plant office, private office and conference room

Background level	SPL dB(A)
Open plant office	45
Cabinet/closed office	39
Conference Room	32

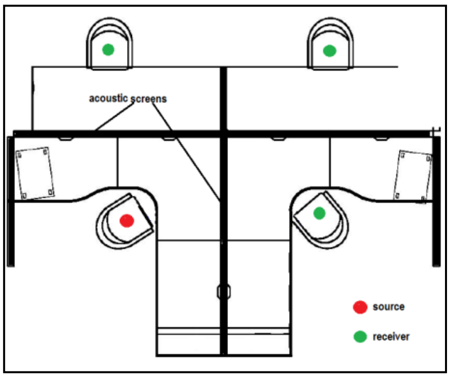
There are chosen and used a few number of measurement points of the appropriate speech levels of talker (or talkers in a conversation) and the background noise level. The positions of sound sources (Fig.3), for briefness are presented only for the case of testing the achieved speech privacy in open plant office (Fig.2 left) and are labeled with red color for the positions and with green color for the positions of sound receivers.

Figure 2 Open plant office - left, private office – center and conference room - right, chosen as three testing places to estimate the achieved speech privacy applying appropriate sound masking system



After definition of described above initial conditions are carried out the appropriate measurements testing the effectiveness of achieved speech privacy applying appropriate sound masking system.

Figure 3 Positions of chosen measurement points as sound sources (in red) and receivers (in green)



Two objective measurements for estimation the effectiveness of the achieved speech privacy in open plant office are used: Speech Transmission Index (STI), defined in standard ANSI S3.5 [4] and the equations (5, 6, 7 and 8) and Privacy Index (PI), defined in standard ASTM E1130 [5] and the equations (9 and 10).
First are prepared the tests to determine speech privacy without using sound masking system carried out the measurements of Speech Transmission Index (STI) and Privacy Index (PI). The results as retrieved data from the experiments without using masking system are presented on Table 3. It's obvious that in the open plant office the privacy and STI are very poor.

Table IIII Results from speech privacy tests without using sound masking system

Type of Premises	ASTM - PI	Subjective	ANSI - STI	Subjectiv e
Open Plant Office (averaged)	51%	No privacy	0.55	Fair
Private Office	72%	Unacceptable privacy	0.67	Good
Conference Room	63%	Unacceptable privacy	0.45	Poor/ Fair

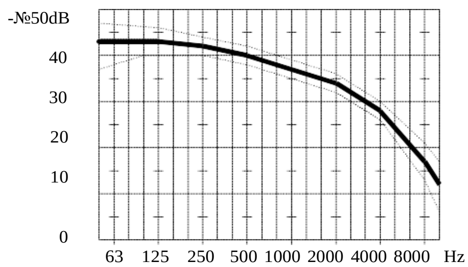
The reason for that is complex but includes poor acoustic treatment, low distance between desks, high background noise and other low impact factors. The proof for that is Table 4 that shows the level of background noise and NR for different premises. The data from other two premises shows logical results and the most convenient room is the private office who has PI=72% and STI=0.67.

Table IV Measured sound levels of background noise and noise reduction (NR)

Type of Premises	Background noise (dBA)	NR (dBA)
Open Plant Office	41	12
Private Office	36	15
Conference Room	35	12

Then are prepared the measurements of Speech Transmission Index (STI) and Privacy Index (PI) to determine speech privacy with using sound masking system, built from processor, amplifier and ceiling speakers mounted inside the suspended ceiling. This is the most effective placement of the speakers because it is easy to achieve diffuse sound field. The spectrum of the using masking signal is defined in standard ANSI S3.5 [4]. The masking signal is generated from sound masking system and emitted from the ceiling speakers as noise sound waves and is shown on Fig.4. The conditions and concrete definition in standard ANSI S3.5 [4] of sound levels of masking signal, given on Fig.6, are compliant with the appropriate building medium used for treatment in open-plan spaces, i.e. the screens with high of 25 – 30 cm, some reflective surfaces, and moderate furniture absorption. These conditions are satisfied for the tested in this article three different premises in typical office building: the open plant office (Fig.2 left), private office (Fig.2 center) and conference room (Fig.4 right).

Figure 4 Spectrum of the using masking signal generated from sound masking system



The important characteristic for the effectiveness of sound masking is the choice of slightly increase (2 dB) at 2000 Hz of the masking signal spectrum level, made because the spectral part of sound masking signal in the frequency band near the frequency 2000 Hz contributes most to speech intelligibility and the spectrum in this frequency band results in fairly neutral masking sound quality. Some tolerances (the dotted-line curves on Fig.4) in the spectrum of sound masking signal are added to realize the possibility of adjusting the used, in concrete sound making situations, levels of the spectrum of sound masking signal, especially for the so called "good open plan spaces", i.e. the relatively larger free spaces in open offices of this type.

The mentioned above definitions of sound masking system and masking sound signal are applied in the tests to determine speech privacy with the measurements of Speech Transmission Index (STI) and Privacy Index (PI). The following results of the measured Speech Transmission Index (STI) and Privacy Index (PI) are shown in Table 5 and are compared with the results on Table 3 (without using sound masking):

- speech privacy using sound masking in the open plant office (Fig.2 left) is 20% greatest (Table 5) in comparison of the tests without sound masking (Table 3), but still has unacceptable speech privacy (Table 5);
- although the sound masking is applied, the Speech Transmission Index (STI) goes down, because the interference of masking signal with the speech signal, causing a blurring effect on the speech;

Table V Results from speech privacy tests with using sound masking system

Type of Premises	ASTM - PI	Subjective	ANSI - STI	Subjective
Open Plant Office (averaged)	70%	Unacceptable privacy	0.47	Fair
Private Office	80%	Normal privacy	0.54	Good
Conference Room	79%	Unacceptable privacy	0.40	Poor

- the private office (Fig.2 center) and conference room (Fig.2 right), also has an improvement in their values of Speech Transmission Index (STI) and Privacy Index (PI) with sound masking system on;
- following differences are achieved in sound pressure levels (SPL), applied in the open plant office (Fig.2 left) - 44 dB(A), private office (Fig.2 center) -39 dB(A) and conference room (Fig.2 right) - 38 dB(A).
These differences look small, chosen in laboratory environment to be + 3 dB(A) above the levels of background noise (see Table 4), while in real open plant offices is recommended to choose and start from -10 dB(A). The reason for that is to learn the auditory hearing perception system of the employees or working people to habituate with level of sound masking signal, which has no speech information itself, therefore it is needed only some time for human hearing perception system and the human brain to get adjusted and accustomed.

IV. Conclusion

The mains conclusions in the realization the goal in this article are the followings:
- there are proposed to use two objective ways for effectiveness estimation of the achieved speech privacy in open plant offices calculating Speech Transmission Index – STI and Privacy Index – PI and also the subjective speech privacy estimation as the mean to analyze and compare the results from objective speech privacy estimations;
- it is shown the benefit using sound masking system to increase the speech privacy in all three premises;
- the achieved speech privacy using sound masking system can be estimated correctly from the measured values of STI and PI obtained in all of the examined premises and correspond well to the subjective estimations;
- it is not possible for all premises to adjust the sound masking level to the subjective perception for all employers, therefore it is recommended, for each concrete type of open office and individually for each person, to choose the concrete way of adjust the suitable sound masking level, to achieve an satisfactory speech privacy.

V. References

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VI. Acknowledgments

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