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Peculiarities of a Rarely Used Method of Measuring the Speech Transmission Index in Premises

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ABSTRACT

Evaluation of speech transmission index (STI) in premises allows for determining the speech intelligibility, and therefore the suitability of premises for speech communication. STI measurements using the speech transmission index for telecommunication systems (STITEL) method are rarely performed in rooms, possibly due to insufficient information on the accuracy of this method. In this paper, computer simulations were used to estimate the STI estimation errors by the STITEL method under conditions of noise and reverberation. The pink noise model and the room impulse response estimate of a real room with a reverberation time T60=0.8 s were used for the research. The duration of the test signals varied between 4, 8, 16, 32, and 64 seconds, and the signal-to-noise ratio varied from minus 28 dB to plus 28 dB. The dependences of the bias, standard deviation, and total error of the STI estimate on the duration of the test signal and the signal-to-noise ratio are obtained. It is shown that the total error of the STI estimation is close to 0.03 when the duration of the test signal is 8 s. Under conditions of noise action, this error decreases with a further increase in the duration of the test signal. Under conditions of joint action of noise and reverberation, such a decrease was not observed, while the total error is within 0.03-0.04.

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1. Introduction

Assessment of speech intelligibility in places with large crowds of people (train stations, airports, malls) is relevant because it is aimed at increasing the level of safety of people inside these places [1-3].

In addition, the assessment of speech intelligibility is important in educational institutions, as it is aimed at the correct and complete perception of information contained in speech. This means the architects and designers must be guided by the requirements of the acoustic passport when designing new educational premises. In addition, this means the administration of educational institutions should pay considerable attention to the acoustic examination and certification of the educational premises in use.

Important results in the form of quantitative estimates of the degree of influence of noise and reverberation on speech intelligibility in educational premises are given in [4-7]. In these studies, it was experimentally shown that noise interference is significantly more dangerous than reverberation. The reason for this situation is the closeness of the main sources of noise, which are nearby sitting students. At the same time, the reverberation time in educational premises rarely exceeds 1 s. This means that the diffuse part of sound reflections (late reverberation), has a relatively low intensity and therefore has a weak masking effect.

Another important result of studies [4-7] is the quantitative assessment of the dependence of speech intelligibility on the age of listeners. It was shown that to achieve verbal intelligibility of 95% for 6-year-old schoolchildren, the signal-to-noise ratio (SNR) should be at least 16 dB, for 11-year-old schoolchildren the threshold can be lowered to 9 dB, and for students - to 1 dB.

The results of the study of large lecture halls equipped with sound amplification systems and induction loops to help students with impaired hearing were presented in the study [8]. At the same time, it was stated the noise level should be within 30-40 dBA, the voice signal level should be 65-75 dBA, and the reverberation time in rooms with a volume of up to 1000 m3 should not exceed 0.8 s. When evaluating speech intelligibility, it was recommended to ensure the value of the STI index > 0.56.

In the study [9], the characteristics of a large lecture hall were evaluated both by computer simulation (ODEON software) and by measuring several acoustic parameters, including the STI.

The results of the assessment of the acoustics of three lecture rooms at Lund University (Sweden) [8] indicate the issue of the increasingly widespread use of audiovisual techniques in rooms not designed for this.

A general drawback of studies [8-10] is the predominant attention to the reverberation action, while [4-7] convincingly proved the more important role of noise interference. At the same time, in all the works mentioned above, there are no clear recommendations on the selection of evaluated parameters for the acoustic certification of premises.

For specialists in the field of acoustic measurements, an important issue is the rational choice of the STI measurement method, taking into account the duration and accuracy of measurements.

A significant drawback of the most accurate FULL STI measurement method [11] is the significant duration of measurements, close to 16 minutes. The STIPA and STITEL methods are much faster, where the measurement duration is about 10-15 s when using one test signal [11]. Given the significant advantages in the speed of measurements, it is recommended in [11] to measure STI in rooms using the STIPA method.

It is stated in [11] the STITEL method can also be used if necessary. However, there are no specific values of the STI estimation errors inherent in the STITEL method in [11]. Thus, the degree of loss of accuracy compared to FULL STI measurements is not clear.

The analysis of literary sources shows the STITEL method is "not very often", if not extremely rarely, used for indoor STI measurements [12-14]. It can be assumed that the reason for this situation is insufficient study of using the STITEL method in rooms. In addition, it can be assumed the insufficient study of the STITEL method is caused by the existence of competitive fast indirect STI measurement methods [15-18], which are currently implemented in several hardware and software applications [19-23].

Thus, it can be stated that the issue of methodical error of STI assessment in conditions of noise and reverberation remains insufficiently covered in literature sources. The objective of the paper is to eliminate this shortcoming.

2. Research Organization

When measuring STI using the STITEL method [11], a broadband test signal is used

$$x(t) = \sum_{k=1}^{7} x_k(t), \qquad x_k(t) = \xi_k(t)\sqrt{f_k(t)}, \tag{1}$$

$\xi_k(t)$ is band-limited noise in the *k*th frequency channel obtained by filtering noise with the speech spectrum, $f_k(t) = 1 + sin\,2\,\pi F_k t$ is modulation function, F_k are modulation frequencies (Table **1**).

Table 1: Modulation frequencies of the STITEL method [11].

k	1	2	3	4	5	6	7
Octave band (Hz)	125	250	500	1000	2000	4000	8000
F_k (Hz)	1.12	11.33	0.71	2.83	6.97	1.78	4.53

At the point in the room where the listener is located, the signal $y(t)$ received by the microphone is used to calculate the modulation transfer coefficients

$$m_k(F_i) = \frac{|A_k(F_i)|}{0.5 \cdot A_k(0)}, \qquad A_k(F_i) = \frac{1}{T}\int_0^T y_k^2(t) e^{-j2\pi F_i t} dt, \tag{2}$$

$y_k(t)$ is response of the *k*th octave filter to the signal $y(t)$.

The modulation transfer coefficients $m_k(F_i)$ are used to calculate the STI:

$$STI = \sum_{k=1}^{7} \alpha_k \cdot MTI_k - \sum_{k=1}^{6} \beta_k \cdot \sqrt{MTI_k \cdot MTI_{k+1}}, \tag{3}$$

$$MTI_k = TI_{k,i=k} \tag{4}$$

$$TI_{k,i} = \begin{cases} \frac{SNR_{eff\ k,i}+15}{30}, & -15 < SNR_{eff\ k,i} < 15; \\ 0, & SNR_{eff\ k,i} \le -15; \\ 1, & SNR_{eff\ k,i} \ge 15; \end{cases}, \tag{5}$$

$$SNR_{eff\ k,i} = 10\,lg\,\frac{m_k(F_i)}{1 - m_k(F_i)}, \tag{6}$$

MTI_k is a modulation transfer index in *a k*th frequency band, α_k and β_k are the weight coefficients, $TI_{k,i}$ is a transfer index, $SNR_{eff\ k,i}$ is an effective signal-to-noise ratio (SNR), $|\cdot|$and is a module symbol.

The research was carried out using computer simulation. The signals $y(t) = x(t) \otimes h(t) + n(t)$, $h(t)$ is RIR, $n(t)$ is stationary pink noise, were generated with a sampling frequency of 22050 Hz. One of the RIR estimates of the university auditorium in RWTH Aachen University (Germany) with the reverberation time T60=0.8 s [24] was chosen for studies. STI calculations were performed for 100 samples of STI estimates obtained by the STITEL method. For comparison, STI calculations were also performed for 30 samples of STI estimates obtained by the FULL STI method. During each calculation session, the duration *T* of signals was varied to 4, 8, 16, 32, and 64 seconds, and the SNR was varied from minus 28 dB to plus 28 dB in 4 dB steps. For each combination of the SNR and *T* parameters, the bias, standard deviation, and full error of the STI estimates were calculated.

3. Results

3.1. Noise as Interference

First, the results of STI estimation by the STITEL method will be considered for the case where there is no reverberation and the speech signal is distorted only by noise interference.

The graphs of average and standard deviation of STI estimates obtained by the STITEL method are shown in Fig. (**1**). A predictive estimate of STI, obtained under the $SNR_{eff\ k,i} = SNR_{eff\ k}$condition, is shown also in Fig. (**1a**). The$SNR_{eff\ k}$ was calculated according to the method described in [25].

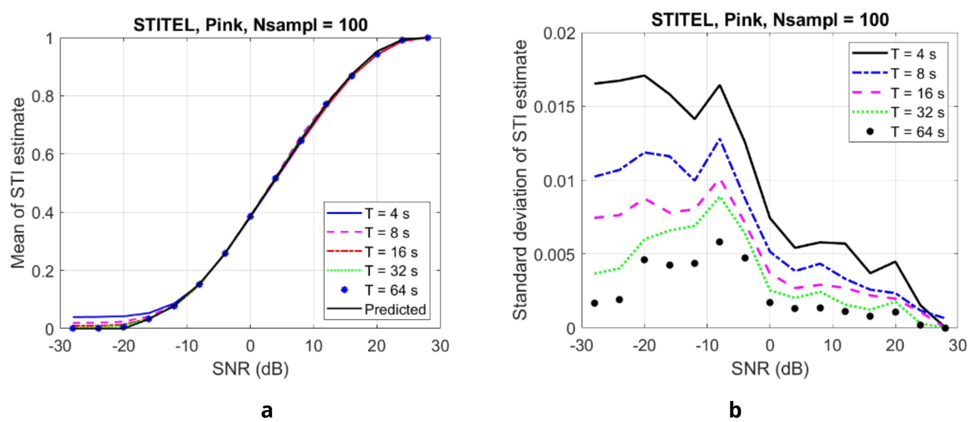


Figure 1: STITEL method: average (**a**) and standard deviation (**b**) estimates of the STI estimates.

Analogous results obtained by the FULL STI method are shown in Fig. (**2**).

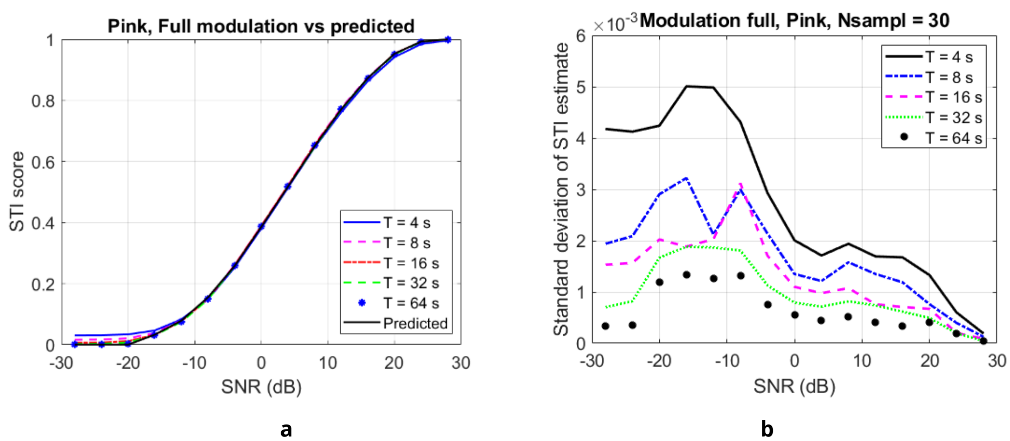


Figure 2: FULL STI method: average (**a**) and standard deviation (**b**) estimates of the STI estimates.

As can be seen from Fig. (**1**) and Fig. (**2**), the STITEL method is significantly inferior to the FULL STI method in terms of standard deviation, but the average values of the STI estimates are quite close.

A quantitative description of the degree of loss of estimation accuracy is given in Fig. (**3**). The graphs of the difference

$$\Delta_{STITEL,predict} = \overline{STI}_{STITEL} - STI_{predict} \tag{7}$$

between the average values of the STI estimates obtained by the STITEL method and the predicted STI estimate are given in Fig. (**3a**), as well as the ratio of the standard deviation estimates for the STITEL method and the FULL STI method

$$\Lambda_{STITEL,FULLSTI} = \frac{\overline{\sigma STI}_{STITEL}}{\overline{\sigma STI}_{FULLSTI}}, \tag{8}$$

are shown in Fig. (**3b**), $\overline{STI}_{STITEL}$ is mean value of STI scores obtained by the STITEL method, $STI_{predict}$ is predictive STI score for the FULL STI method, $\overline{\sigma STI}_{STITEL}$ and $\overline{\sigma STI}_{FULLSTI}$ are estimates of standard deviations for the STITEL method and the FULL STI method, respectively.

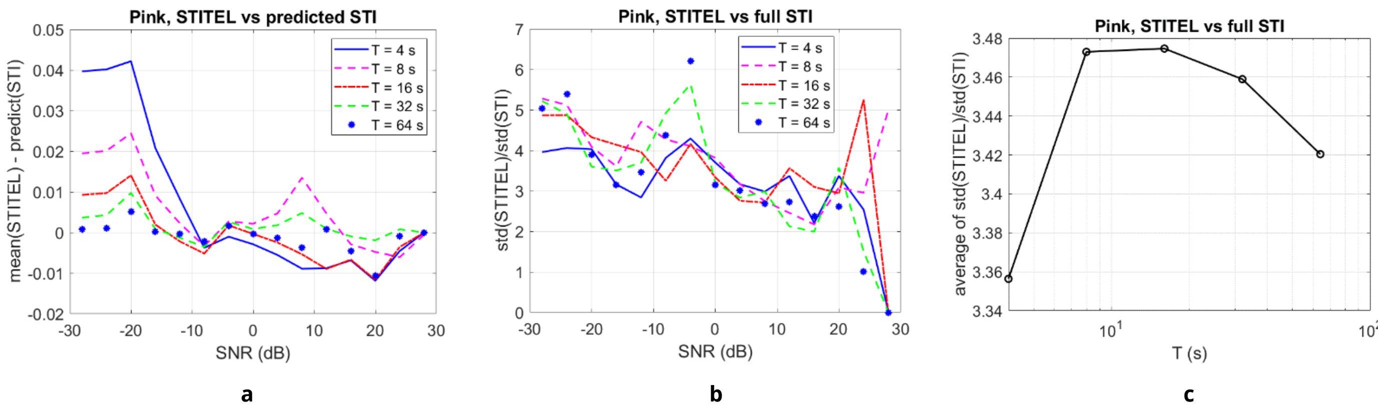


Figure 3: Comparison of STITEL and FULL STI methods: (**a**) difference of average and predicted STI values, (**b**) ratio of standard deviations, and (**c**) average ratio of standard deviations.

As can be seen in Fig. (**3b**), the ratio of standard deviations is quite stable within SNR = -20...+20 dB range. The values of the ratio of standard deviations averaged in this range as a function of the parameter *T* are shown in Fig (**3c**). These ratios depend little on *T*, so it can be assumed that the STITEL estimate loses about 3.5 times the FULL STI method in terms of standard deviation.

3.2. Noise Plus Reverberation as Interferences

Graphs of the average and standard deviation of the STI estimates obtained by the STITEL method for the case of the joint action of noise and reverberation are shown in Fig. (**4**). The RIR estimate of the RWTH Aachen University (Germany) auditorium with the reverberation time T60=0.8 s was chosen for the research [24].

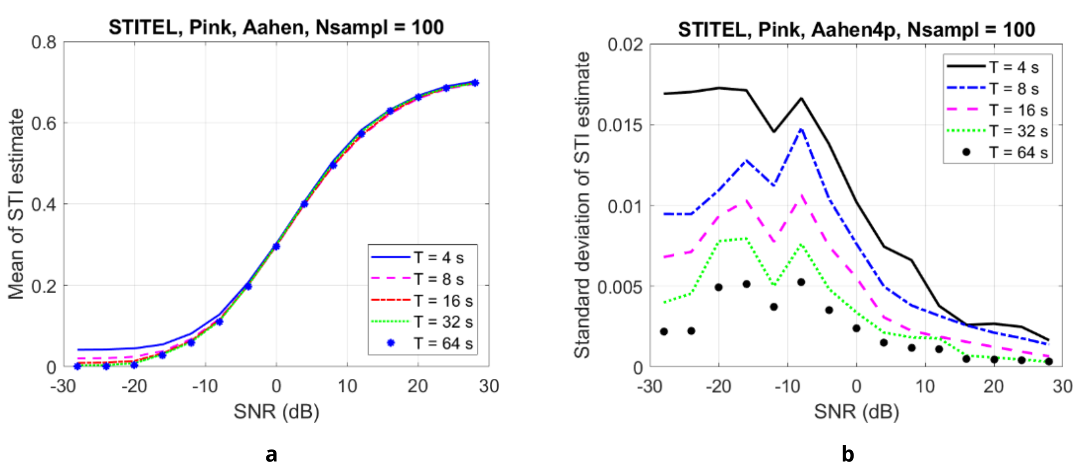
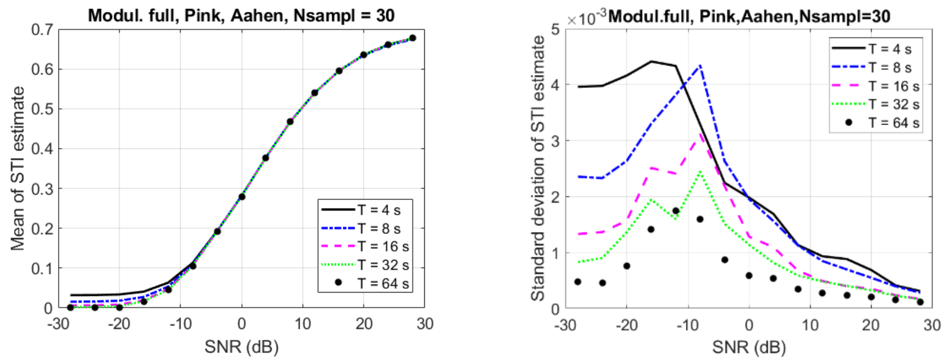


Figure 4: STITEL method: average (**a**) and standard deviation (**b**) estimates of the STI estimates.

Similar results obtained by the FULL STI method are shown in Fig. (**5**).



a **b**

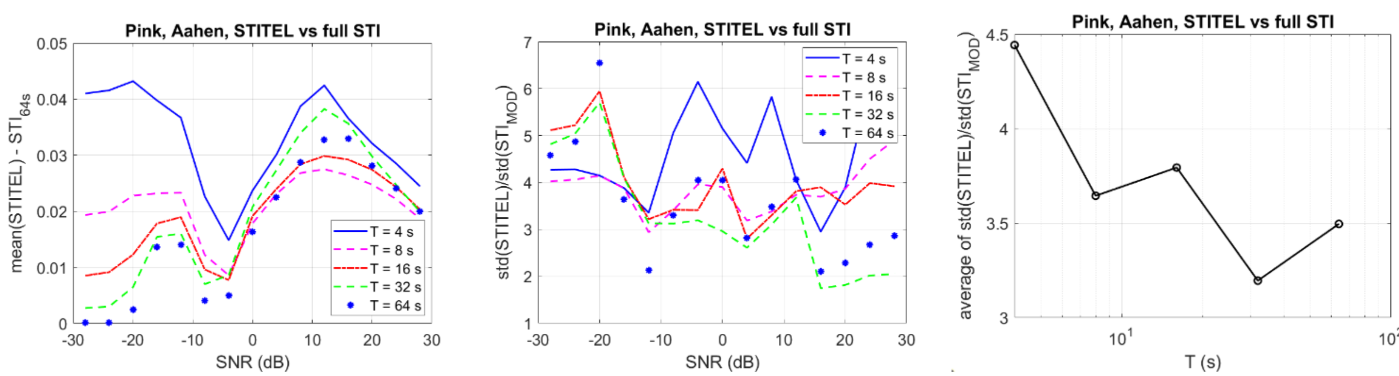
Figure 5: FULL STI method: average (**a**) and standard deviation (**b**) estimates of the STI estimates.

It can be seen from Fig. (**4**) and Fig. (**5**) the STITEL method is noticeably inferior to the FULL STI method in terms of the standard deviation of the STI estimate, although the average values of the STI estimates appear to be quite close. The graphs of bias estimates

$$\Delta_{STITEL,STI} = \overline{STI}_{STITEL} - STI_{T=64s} \tag{9}$$

are shown in Fig. (**6a**). As can be seen, the STI estimates $STI_{T=64s}$obtained by the FULL STI method for *T*=64 s were used as STI reference values in (9). It can be noted in justifying such actions that the accuracy of the STI prediction method proposed in Appendix L [11] is unknown. At the same time, an increase in the accuracy of the FULL STI method with an increase in the duration of the test signal is an indisputable fact.

As can be seen from Fig. (**6a**), the STITEL method leads to significantly overestimated STI values in the presence of reverberation. The graphs of the ratio (8) for estimates of the standard deviations of the STITEL method and the FULL STI method are shown in Fig. (**6b**). The values of ratio (8) averaged over the interval SNR=-20...+20 dB for different *T* are shown in Fig. (**6c**). As in the case of the action of noise alone, it can be assumed that the STITEL estimate is about 3.5 times worse than the FULL STI method by standard deviation.



a **b** **c**

Figure 6: Comparison of STITEL and FULL STI methods: (**a**) difference of average and "predicted" STI values, (**b**) ratio of standard deviations, and (**c**) average ratio of standard deviations.

4. Discussion

For the case of noise, the maximum bias value $|\Delta|$, the maximum standard deviation value Σ and maximum total error values $\Omega = \sqrt{\Delta^2 + \Sigma^2}$ in the range of SNR=-28..+28 dB are given in Table **2**.

Table 2: Comparison of STITEL and FULL STI methods for the noise case.

Method	T (s)	$\|\Delta\|$	Σ	Ω
FULL STI	4	0.034	0.005	0.034
	8	0.021	0.003	0.021
	16	0.011	0.003	0.012
	32	0.007	0.002	0.007
	64	0.005	0.001	0.005
STITEL	4	0.042	0.017	0.045
	8	0.024	0.013	0.028
	16	0.014	0.010	0.017
	32	0.010	0.009	0.013
	64	0.011	0.006	0.012

The value of just noticeable difference JND=0.03 [26] is considered to be an acceptable error for STI estimation for practical use. Therefore, the value T = 8 s can be considered acceptable for practical use of the STITEL method, since $|\Delta|$=0.024, Σ =0.013, and Ω =0.028. The value T=16 s is more acceptable, since in this case $|\Delta|$=0.014, Σ =0.010, Ω =0.017.

The maximum errors$|\Delta|$, Σ andΩ for the case of simultaneous action of noise and reverberation are given in Table **3**.

Table 3: Comparison of STITEL and FULL STI methods for the noise and reverberation case.

Method	T (s)	$\|\Delta\|$	Σ	Ω
FULL STI	4	0.032	0.004	0.032
	8	0.016	0.004	0.016
	16	0.007	0.003	0.008
	32	0.003	0.002	0.004
	64	0	0.001	0.001
STITEL	4	0.043	0.017	0.047
	8	0.028	0.015	0.031
	16	0.030	0.011	0.032
	32	0.038	0.008	0.039
	64	0.033	0.005	0.033

Comparing the$|\Delta|$, Σ andΩ values given in Tables **2** and **3** for the STITEL method, it can be seen that in the case of the combined effect of noise and reverberation, the$|\Delta|$ values first decrease with increasing T, but then increase again. This behavior is significantly different from one for the action of noise alone. At the same time, theΣ values in both cases are close. After all, we can consider the values T=8 s and T=16 s to be acceptable for practical use. A further increase in the duration T of the test signal is impractical, as it does not lead to a decrease in the total estimation error.

In the future, it is advisable to consider several samples of RIR assessment, which differ significantly in terms of reverberation time and frequency dependence.

In addition, it would be appropriate to investigate the influence of the shape of the long-term speech spectrum on the results of STI evaluation by the STITEL method. Until now, several works can be cited where the results of research into the long-term spectrum of speech are presented [27-30]. Thus in particular it was noted in [27] that it is desirable to take into account the difference between the speech spectra of men and women, as well as the speech spectra of different languages and dialects. It is proposed in [28] to use a new form of the spectrum of English speech of men instead of the one proposed in the standard [11]. In [29], the results of the spectrum assessment of various languages, and in particular, Ukrainian speech, are given. Thus, the task of researching the influence of the shape of the long-term speech spectrum on the results of STI evaluation by the STITEL method appears to be relevant.

Another important area of research is the evaluation of STI by the STITEL method outside the meeting rooms. Usually, materials with high soundproofing properties are used when arranging such rooms [31]. The definition of speech intelligibility in religious buildings is also an important issue [32].

A certain advantage of the subjective assessment of the room's acoustic properties [33] is the possibility of obtaining reliable measurement results thanks to the use of the human auditory system. However, the significant duration and cost of such an approach eventually force one to turn to the use of objective methods and, in particular, the STITEL method.

Since the reverberation of the room contributes to the surround perception of sound [34, 35], two-channel measurement of speech intelligibility by the STITEL method using an artificial head [24] may be a promising direction for research.

5. Conclusion

Objective (instrumental) methods of evaluating speech intelligibility in rooms are much cheaper and faster than subjective methods. Today, there are several methods of objective assessment of speech intelligibility indoors, and the STITEL method is one of the simplest. This method is also very fast since its implementation demands a short test signal of no more than 10 seconds. However, the practical use of the STITEL method is complicated by the fact that the methodical error of the assessment remains unknown.

In this paper, computer simulations were used to estimate the STI methodical estimation errors by the STITEL method under conditions of noise and reverberation. The dependences of the bias, standard deviation, and total error of the STI estimate on the duration of the test signal and the signal-to-noise ratio are obtained. It is shown that the total error of the STI estimation is close to 0.03 when the duration of the test signal is 8 s. Under conditions of noise action, this error decreases with a further increase in the duration of the test signal. However, under the conditions of the joint action of noise and reverberation, such a decrease is not observed, and the total error is within 0.03-0.04 for the signal-to-noise ratio in the range from minus 28 dB to plus 28 dB.

Conflict of Interest

The authors declare that there is no conflict of interest.

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