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Effect of Highpass Filtering on the Speech Transmission Index

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Abstract Highpass filters are commonly used in the signal chain of public address systems. One of the reasons for using a highpass filter is to protect the loudspeaker from unwanted low-frequency signals. In addition, it can increase the intelligibility of speech. In this paper, the effect of the cutoff frequency and order of a highpass filter on the speech transmission index, the crest factor, and the sound level are presented. Analyses were performed for an ideal transmission channel, taking into account reverberation time, interfering noise, and high levels of sound. A computer model of the public address system developed by the author, based on the direct STIPA method, was used. This model enables analyses in the nonlinear range of power amplifier operation, which is often used in public address systems but is not considered in commercially available simulation programs.

Keywords: speech transmission index, STIPA, public address system, highpass filter.

1. Introduction

The effect of highpass filtering on speech intelligibility has been the subject of research for several decades. Originally, this research focused on the generalized communication channel [1-8]. Then they began to be carried out in the context of narrower applications, such as audiology [9-10]. This has made it possible to take into account the application-specific properties of the transmission channel. The purpose of using highpass filtering is mainly the enhancement of speech intelligibility in high noise levels. Among other things, it is also used for this purpose in sound systems, which this work focuses on.

The specificity of public address (PA) systems is that reverberation time and specific spectra, and interfering noise levels must be taken into account. High levels of interfering noise require the message to be reproduced at levels much higher than typical speech levels, which also affects intelligibility. Additionally, unlike typical telecommunications and audiology applications, it is necessary to acoustically transmit messages over large areas. Therefore, for economic reasons, this may require the operation of power amplifiers and loudspeakers in a nonlinear operating range. In studies on the effect of highpass filtering on speech intelligibility, it was assessed using subjective methods or objective methods such as articulation index or speech intelligibility index. In this paper, as a speech intelligibility measure, the speech transmission index for public address systems STIPA (speech transmission index for public address systems) was used [11]. Speech transmission index STI is a method based on the work of Houtgast and Steeneken and has been in development for about 50 years [12-14]. STIPA is a condensed version of the Full STI and is currently probably the most popular method used in Europe to assess the speech intelligibility of PA systems. In many countries, STIPA is the main quality criterion in formal requirements for voice alarm systems or railway passenger information systems.

The effect of reverberation time on speech transmission index has been studied, among others, by Houtgast et al. [11]. The effect of the signal level on speech intelligibility has been studied, among others, by Pollack and Pickett [3]. Brachmanski used pink noise as an interfering noise in his studies [7, 8], which is more suitable for sound systems than white noise commonly used in the analysis of communication channels. The effect of the peek clipping on speech intelligibility was studied by Licklider and Polack [1], Thomas and Niederjohn [4] and Dziechciński [15]. However, there have been no studies combining the effects on STIPA of highpass filtering, signal-to-noise ratio, reverberation time, and high signal levels with the nonlinear properties of the power amplifier, which is the subject of this paper.

In sound systems, highpass filtering can also have other applications. One of these is protection against the transmission of unwanted low-frequency signals. This uses a highpass filter (HPF) inserted in the signal chain directly behind the signal source. The HPF cutoff frequency is selected based on the transmitted signal's spectrum or the frequency range important for the signal. In the case of a microphone used for speech, such a filter can be built directly into the microphone or at the beginning of the microphone input of an audio mixer. The typical cutoff frequency of this filter is 80-100 Hz. Driving the loudspeaker by a signal with frequencies below its lower limit of the effective frequency range can cause it to be a source of increased nonlinear distortion, and, at a high signal level, it may even be damaged. Another application of HPF is the protection of loudspeakers before such signals. The HPF cutoff frequency depends on the loudspeakers used in the system. For very large loudspeakers for tour sound systems, this may be 20-30 Hz. The lower limiting frequencies of the useful frequency range of small loudspeakers used in public address systems are much higher. Especially in the case of horn loudspeakers, where these can be above 400 Hz.

2. Research design

The reduction of the signal spectrum in the high-frequency range is associated with a degradation of speech quality and intelligibility, also at relatively high cutoff frequencies [16]. Limiting the bandwidth of a transmission channel in the low-frequency range may degrade quality, but may not necessarily decrease speech intelligibility. On the contrary, in some cases, it can increase it. This is because 56% of the standardised male speech power (IEC 60268-16:2020 [11]) is contained in the 1/1 octave bands 125 Hz and 250 Hz. The contribution of these bands to speech intelligibility is much lower [14]. It is generally accepted that the largest contribution to speech intelligibility is in the frequency range close to the analogue telephone band (300 - 3400 Hz). By limiting the signal spectrum in the low-frequency range, it is, therefore, possible to increase the signal-to-noise ratio *SNR* in the range of the 1/1 octave bands from 0.5 to 4 kHz, which is more important for speech intelligibility. The same is true for face-to-face communication, where, in the case of a very high level of interfering noise, we not only increase the level of speech, but at the same time change its spectrum [17]. For interfering noise with a sound level of $L_{\mathrm{Aeq},n}$ = 76 dB and a pink noise spectrum, this situation is presented in Fig. 1 ("Pink noise"). The spectrum of the male shout signal [17] is mainly concentrated in the 1/1 octave bands from 0.5 to 2 kHz, and in this range signal levels are 10 dB higher than the interfering noise (Fig. 1 "Male shout").

In the design of public address systems, the signal-to-noise ratio SNR_A is defined as:

$$SNR_A = L_{\mathrm{Aeq},s} - L_{\mathrm{Aeq},n} \qquad (1)$$

where $L_{\mathrm{Aeq},s}$ is the A-weighted equivalent continuous sound level of speech and $L_{\mathrm{Aeq},n}$ is the A-weighted equivalent continuous sound level of interfering noise. A simple engineering assumption used in the design of public address systems is that SNR_A should be not less than 10 dB. With this approach, a signal with a normalised male speech spectrum and $L_{\mathrm{Aeq},s}$ = 86 dB (Fig. 1 "Male IEC") will provide $SNR \geq 10$ dB in the 1/1 octave bands from 125 Hz to 1 kHz bandwidth, but for the very important 2 kHz band we will get $SNR = 5$ dB, and for 4 kHz the signal level will be less than the level of the interfering noise.

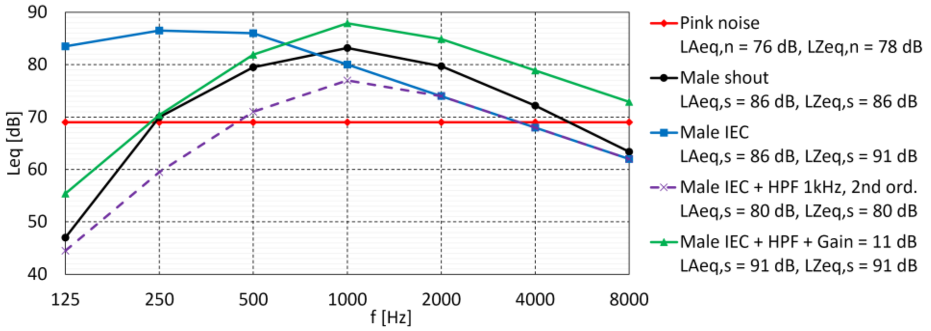

Figure 1. Pink noise, male shout, and IEC male speech spectra without and with HPF.

In public address systems, the signal spectrum can be easily shaped using highpass filtering to achieve an effect similar to that of direct communication. The spectrum of the speech signal after second-order HPF with a cutoff frequency of 1 kHz is shown in Fig. 1 ("Male IEC + HPF 1kHz, 2nd ord."). The signal level of the male speech signal before filtering was $L_{\mathrm{Zeq},s}$ = 91 dB, and after filtering $L_{\mathrm{Zeq},sf}$ = 80 dB. Without changing the power of the signal driving the loudspeaker, it is possible to increase the signal after filtering by 11 dB (Fig. 1 "Male IEC + HPF + Gain = 11 dB"). The signal after such filtering will provide an *SNR* not less than 10 dB in the 1/1 octave bands from 0.5 to 4 kHz and, therefore, particularly important for speech intelligibility. Compared to an unfiltered male speech signal, SNR_A will also increase from 10 dB to 15 dB.

As a speech intelligibility measure, STIPA was used. In the STI algorithm, the contribution of individual 1/1 octave bands to the final score is not a simple weighting relationship [14, 11]. Furthermore, as mentioned earlier, in sound systems, in addition to *SNR,* the final STI score is influenced, among other things, by reverberation time and nonlinear properties of the sound system components. To take these factors into account, the study used an adapted computer model of the sound system based on the direct STIPA method proposed by Dziechciński [17] and took into account the nonlinear operating range of the power amplifier [15]. The effect of the order of the highpass filter and its cutoff frequency on STIPA was analysed for transmission channels with varying properties. An ideal channel, with interfering noise, reverberation and the nonlinear operating range of a power amplifier were studied. The effect of highpass filtering on other signal parameters relevant to sound systems such as crest factor *CF* and A-weighted equivalent continuous sound level was also assessed. A block diagram of the model used for the tests is shown in Fig. 2. The STIPA generator and analyser operate according to IEC 60268-16:2020. Their correct operation was validated according to the guidelines of this standard. The gain control circuit allows the amplifier to be driven in proportion to the peak value of its maximum input voltage limited by distortion. Therefore, a gain of G = 0 dB means the maximum value of the signal without peak clipping.

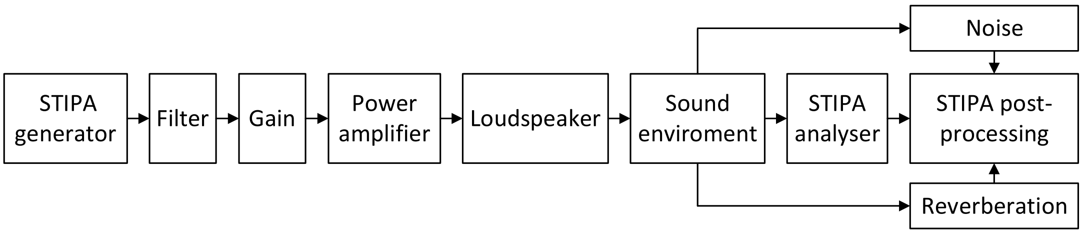

Figure 2. Block diagram of the computer model of the public address system used in this work.

The amplifier was modelled using the relationship proposed by Rapp [19]:

$$y(n) = \frac{K_U \cdot x(n)}{\left(1 + \left(\frac{K_U \cdot x(n)}{U_p}\right)^{2p}\right)^{-2p}}, \tag{2}$$

where $y(n)$ is the output signal, $x(n)$ is the input signal, K_U [V/V] is the voltage gain in the linear range, p is the smoothing factor (p = 280 is a suitable value for class D power amplifiers [15]) and U_p is the peak value of the distortion limited output voltage [15].

It was assumed that the model would use a loudspeaker that does not introduce any linear or nonlinear distortion but is only an electroacoustic transducer. The acoustic environment was modelled by a reverberation time T, whose values in the analysed 1/1 octave bands will be equal. For simplicity, it was assumed that STIPA would be analysed for relatively large source-receiver distances. In this case, the effect of the reverberation time on the modulation transfer function $m_{k,T}$ is independent of the source-receiver distance and the directional properties of the loudspeaker [11] and is described by the formula:

$$m_{k,T}(f_m) = \frac{1}{\sqrt{1 + \left(\frac{2\pi f_m T}{13{,}8}\right)^2}}, \tag{3}$$

where f_m is the modulating frequency. The effect of reverberation time on the modulation transfer function is taken into account in the postprocessing stage. The modulation indices m_k used to determine STIPA, are determined as the product of the modulation index $m_{k,a}$ obtained by analysing the STIPA signal and $m_{k,T}$:

$$m_k(f_m) = m_{k,a}(f_m) \cdot m_{k,T}(f_m). \tag{4}$$

Finally, the STIPA value is calculated according to an algorithm of IEC 60268-16, taking into account the interfering noise levels in 1/1 octave bands. Two extremely different cases of the interfering noise spectrum used in sound systems were used for the analyses, male speech (one of the least disadvantageous cases) and pink noise (one of the most disadvantageous cases). Male speech interfering noise spectrum is the same as standardised IEC male speech [11] and will be named “male noise”.

The analysis was mainly performed for the limit values of the prescriptive design method for voice alarm systems of CEN/TS 54-32 [20] - interfering noise level $L_{\mathrm{Aeq},n}$ = 64 dB, signal level $L_{\mathrm{Aeq},s}$ = 76 dB, reverberation time T = 1.3 s. For small and acoustically adapted rooms, T = 0.6 s was assumed. $L_{\mathrm{Aeq},n}$ = 95 dB was taken as a very high interfering noise level (the highest value encountered by the author in the practice of designing sound systems).

3. Results

Initial tests were performed for highpass filters of orders first to fourth. Analyses were performed as a function of the filter cutoff frequency f_{HPF} in the range from 100 Hz to 10 kHz with 1/6 octave resolution. It was verified that the type of HPF did not affect the STIPA values obtained. Butterworth filters were used for further analyses.

In the first step, the effect of the order and f_{HPF} of the filter on STIPA was investigated for an ideal transmission channel. Thus, it was assumed that the power amplifier operates in a linear operating range (G = 0 dB), and the reverberation time T = 0 s and interfering noise is negligible. To make the STIPA result independent of signal level, auditory effects were excluded from the model. The results of these analyzes are shown in Fig. 3a. The first-order filter for the ideal channel does not introduce a significant reduction in STIPA values for the entire analysed range of its cutoff frequencies. The same is true for second and third-order filters with cutoff frequencies up to 2 kHz. In the case of the fourth-order filter, the effect on STIPA is greater, but for cutoff frequencies up to 1 kHz, it only slightly exceeds 0.01.

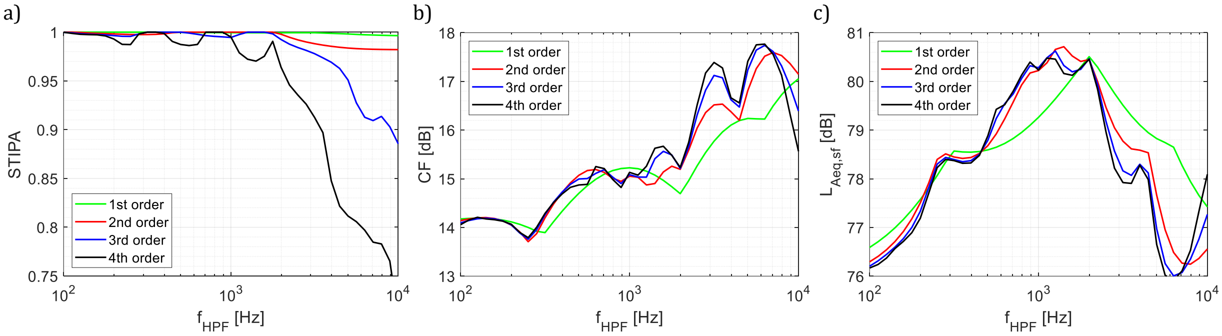

Figure 3. Effect of cutoff frequency and filter order for an ideal transmission channel ($L_{\mathrm{Aeq},s}$ = 76 dB, T = 0 s, G = 0 dB) on: a) STIPA, b) crest factor, c) sound level.

Limiting the spectrum of a signal affects the peak values of the signal (Gibbs phenomenon) and thus its crest factor CF *is* defined as:

$$CF = 20 \cdot \log \frac{x_{\mathrm{TP}}}{x_{\mathrm{RMS}}} = L_{\mathrm{TP}} - L_{\mathrm{Zeq}} \tag{5}$$

where x_{TP} is the true peak [20] value of a voltage or sound pressure and x_{RMS} is the RMS value. Proportionally to the increase CF, the RMS values of the signal level obtained at the output of a power amplifier operating linearly decrease. The CF of the unfiltered STIPA signal used for the tests is 14 dB. The CF values of this signal for the filters tested are shown in Fig. 3b. Filtering for f_{HPF} from 100 Hz to 300 Hz changes the CF to ±0.3 dB, i.e. to a negligible extent. For f_{HPF} from 500 Hz to 1.2 kHz, the crest factor increases to +1 dB, which can be a noticeable value. A significant increase in CF greater than 2 dB applies to f_{HPF} above 2 kHz for filters of orders from second to fourth and above 3 kHz for the first order.

The negative effect on the output signal level of an increase in the crest factor is compensated in excess by the possibility of shifting the energy of the speech signal into the higher frequency range as described in Section 2. The effect of the order and f_{HPF} of the filter on the A-weighted equivalent continuous sound level of the STIPA signal after filtering $L_{\mathrm{Aeq},sf}$ is shown in Fig. 3c. The resulting sound level values take into account the already increased CF of the signal. The sound level of the signal without $L_{\mathrm{Aeq},s}$ filtering for the case presented was 70 dB. For f_{HPF} above 250 Hz, the increase in sound level exceeds 2 dB, for f_{HPF} above 500-800 Hz (depending on the filter order) it exceeds 3 dB, and above 800 Hz even 4 dB.

According to research by Dziechciński [15] overdriving the power amplifier to 5 dB does not significantly affect STIPA values. These studies were conducted for a full-band STIPA signal. Fig. 4 shows the effect of amplifier overdrive for filters first to third order with f_{HPF} equal to 300, 600 and 1200 Hz and an unfiltered signal (in Fig. 4 "HPF off"). For the first-order filters (Fig. 4a), the gain limit above which STIPA starts to decrease noticeably is, as for the unfiltered signal, G = 5 dB. The same is true for second-order filters (Fig. 4b), except for the filter with f_{HPF} = 1200 Hz, for which the negative effect on STIPA is greater than the other cases for G in the range of 2 to 7 dB. For third-order (Fig. 4c) and fourth-order filters, practically the entire analysed G range for the filtered signal STIPA is smaller than for the unfiltered signals.

Research by Dziechciński [15] shows that for an unfiltered STIPA signal, for some cases of interfering noise and reverberation time, it may be beneficial to overdrive the amplifier by up to G = 8 dB [15]. In terms of immunity to amplifier overdrive, signals after first-order filtering with f_{HPF} equal to 600 and 1200 Hz seem to be particularly interesting. For these signals, gains of more than 5 dB provide larger STIPA values than for the unfiltered signal. This may be an important property for environments with high levels of interfering noise, which will be investigated later in this paper.

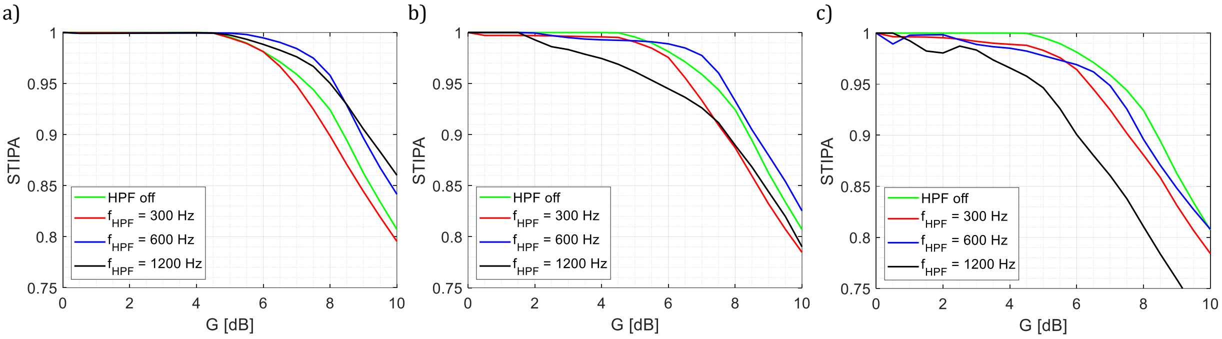

Figure 4. Effect of selected HPF cutoff frequencies and power amplifier drive on STIPA for a) first-order filter, b) second-order filter, c) third-order filter.

For a channel with interfering noise with $L_{\mathrm{Aeq},n}$ = 64 dB, for a signal level without filtering $L_{\mathrm{Aeq},s}$ = 76 dB and taking into account auditory effects in the STI algorithm, the highest STIPA values are obtained for first-order filtering (Fig. 5). For male noise for f_{HPF} = 400-600 Hz (Fig. 5a), and pink noise for f_{HPF} = 2.2 kHz (Fig. 5b). As predicted from the analyzes in Section 2, the effect of highpass filtering is significantly greater for pink noise, with an increase in STIPA from 0.74 to 0.91. For male noise, STIPA increased from 0.87 to 0.93.

For the same signal properties and interfering noise, but including a reverberation time T = 1.3 s, the effect of filtering is shown in Fig. 5c) and d). For male noise, the positive effect of filtering is negligible (Fig. 5c - STIPA maximally increases from 0.50 to 0.51. This is because STIPA is mainly influenced by the relatively high value of the reverberation time, and the SNR in the range of 1/1octave bands important for speech intelligibility is already relatively high (12 dB) in the case of the signal without filtering. In the case of the pink noise, the situation is different (Fig. 5d). STIPA increases from 0.44 to 0.51 for the signal after first-order filtering and f_{HPF} from 1 to 2 kHz.

When the reverberation time and signal-to-noise ratio decrease, the effect of filtering will be greater. For T = 0.6 s and SNR_A = 6 dB this is illustrated in Fig. 5e and 5f. In this case, for male noise STIPA increases from 0.54 to 0.59 (Fig. 5e), and for pink noise from 0.46 to 0.58 (Fig. 5f).

One of the auditory effects modelled in the STI algorithm is the masking phenomenon, which causes increasing sound levels above about 80 dB to reduce speech intelligibility. The effect of f_{HPF} and filter order on STIPA for T = 0.6 s, SNR_A = 6 dB and interfering noise with $L_{\mathrm{Aeq},n}$ = 95 dB is shown in Fig. 5g and 5h. The acoustic conditions are therefore analogous to those presented in Fig. 5e and 5f (the values of T and SNR_A are the same), except that the signal sound level and interfering noise level are 31 dB higher. The STIPA value as a result of highpass filtering for male noise increased from 0.49 to 0.52 and thus 0.02 less than for low levels, where the STIPA increase was 0.05. For the pink noise, STIPA increased from 0.41 to 0.55 and thus 0.02 more than for low levels, where the STIPA increase was 0.12.

The effect of the HPF on STIPA is greater the smaller the SNR_A, which for an HPF of first-order is presented in Fig. 6. The SNR_A also determines the optimum value of f_{HPF}, but over a relatively large range of f_{HPF}, STIPA values are close to the maximum. This optimal range of the f_{HPF} for male noise is from 0.5 to 1 kHz, and for pink noise from 1 to 2 kHz.

In the next step, the effect of the cutoff frequency of the first-order filter on STIPA was checked for G from 5 to 8 dB, for the channel parameters as in the previous two stages of analysis. As can be seen from the characteristics shown in Fig. 7, increasing the gain from 5 to 6-8 dB can increase STIPA. Near the optimum values of f_{HPF} for male noise, the increase is less than 0.01 but for pink noise it is 0.02.

4. Discussion

As shown in the paper, shaping the signal spectrum with highpass filtering for ideal transmission channels can decrease STIPA. However, for public address systems operating in the presence of interfering noise, highpass filtering improves speech intelligibility. Increasing speech intelligibility with highpass filtering is possible by improving the signal-to-noise ratio in the frequency range most important for speech intelligibility. On the other hand, HPF can increase the crest factor of the signal, making it more difficult to perform linear processing in a public address system. As shown (Fig. 3), the CF of the STIPA signal increases as a result of highpass filtering, but despite this, the sound level of the undistorted signal increases by up to

4.5 dB. It has also been shown that a first-order filtered STIPA signal with a sufficiently high cutoff frequency can provide less degradation of STIPA values in the nonlinear operating range of the amplifier than a nonfiltered signal (Fig. 4). This can further increase the system gain in the nonlinear operating range of the amplifier by 2-3 dB and increase the achievable STIPA values by an additional 0.02 (Fig. 7b).

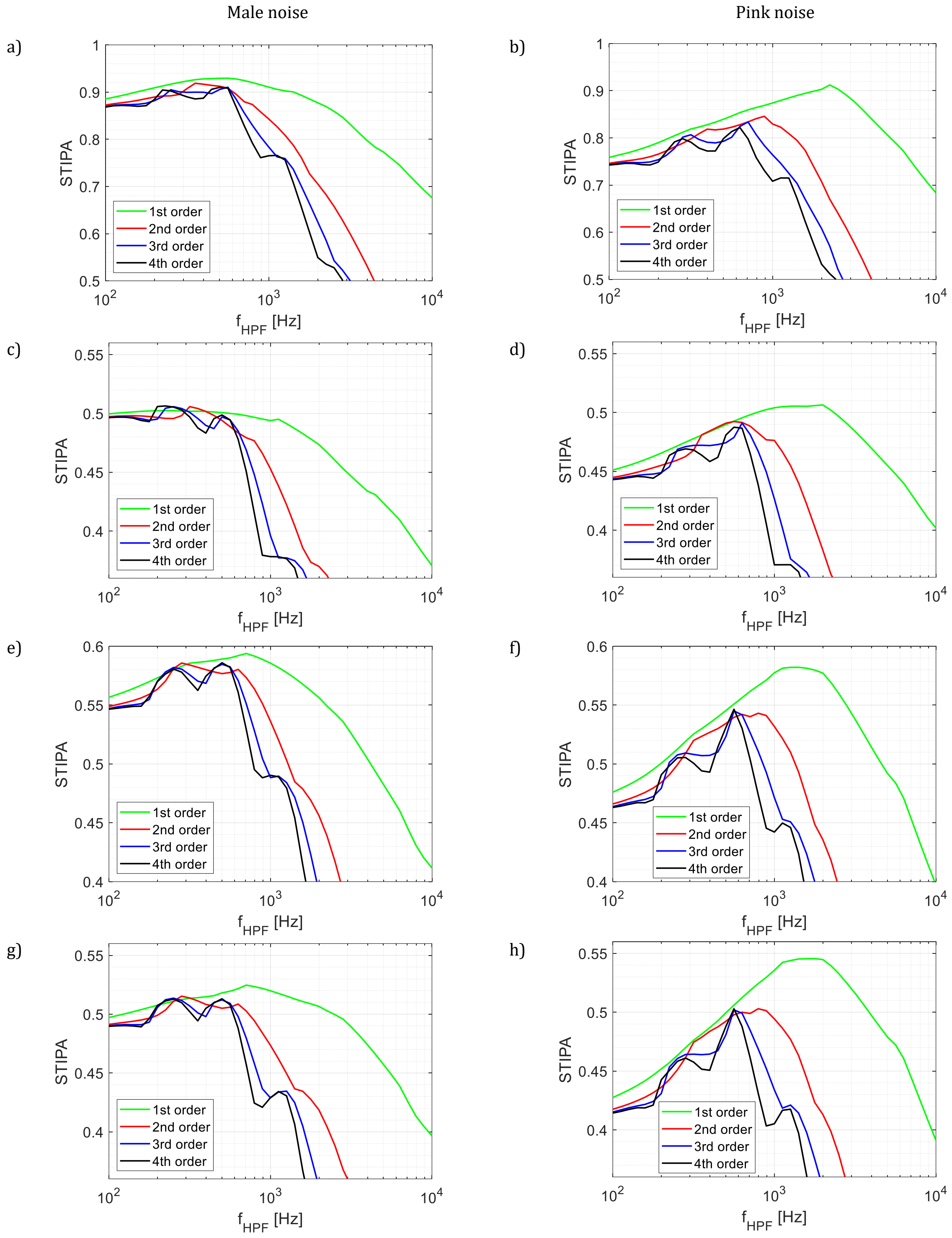

Figure 5. Effect of cutoff frequency and filter order on STIPA, for:
a), b) T = 0 s, G = 0 dB, $L_{\mathrm{Aeq},s}$ = 76 dB, $L_{\mathrm{Aeq},n}$ = 64 dB,
c), d) T = 1.3 s, G = 5 dB, $L_{\mathrm{Aeq},s}$ = 76 dB, $L_{\mathrm{Aeq},n}$ = 64 dB,
e), f) T = 0.6 s, G = 5 dB, $L_{\mathrm{Aeq},s}$ = 70 dB, $L_{\mathrm{Aeq},n}$ = 64 dB,
g), h) T = 0.6 s, G = 5 dB, $L_{\mathrm{Aeq},s}$ = 101 dB, $L_{\mathrm{Aeq},n}$ = 95 dB.

Depending on the interfering noise spectrum, signal-to-noise ratio SNR_A, and reverberation time T, the impact of HPF varies. The smaller SNR_A and T values, the greater the effect of highpass filtering on STIPA. A larger increase in STIPA values, up to 0.17, is obtained for pink noise (Fig. 5b). For male noise, the possible increase can reach 0.06 (Fig. 5a). For male noise for SNR_A above 12 dB, the use of highpass filtering for spectrum shaping is unnecessary (Fig. 5c, Fig. 6a), but for pink noise, the positive effect of HPF on STIPA also applies to SNR_A greater than 15 dB (Fig. 6b). For high levels of male noise, the effect of HPF on STIPA is smaller than for low levels (Fig. 5g and Fig. 5e), while for pink noise, the effect is larger than for low levels (Fig. 5h and Fig. 5f). For the cases analysed, the differences between the maximum STIPA values were 0.02. The analyzes show that the best results in shaping the signal spectrum are obtained in most cases for first-order filtering. Niederjohn obtained a similar result despite the use of different interfering noise and SNR [6]. Thomas' research [5] indicated that a third-order filter with a cutoff frequency of 1500 Hz was optimal. However, for the two interfering noise spectra studied, the highpass filter cutoff frequency that provides the maximum STIPA value differs significantly. For the male noise, this frequency is in the range of 500-800 Hz, while for the pink noise it is 1-2 kHz. For other interfering noise spectra using the described methodology, the optimum cutoff frequency can be determined.

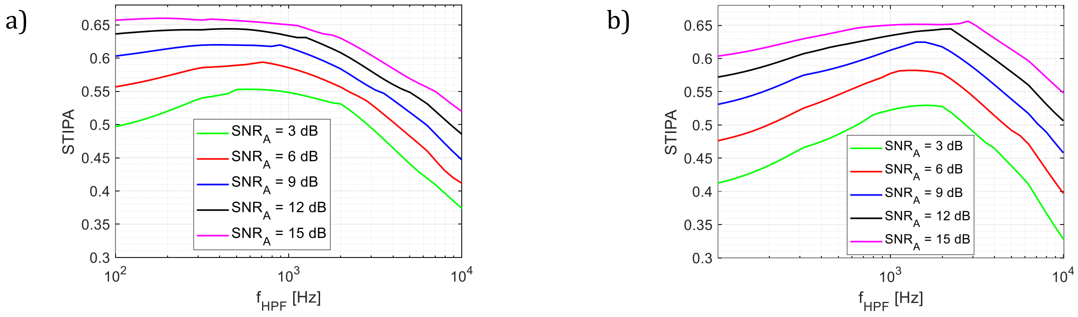

Figure 6. Effect of the first-order filter cutoff frequency on STIPA for selected signal-to-noise ratios SNR_A, for T = 0.6 s, G = 5 dB, $L_{\mathrm{Aeq},n}$ = 64 dB and a) male noise, b) pink noise.

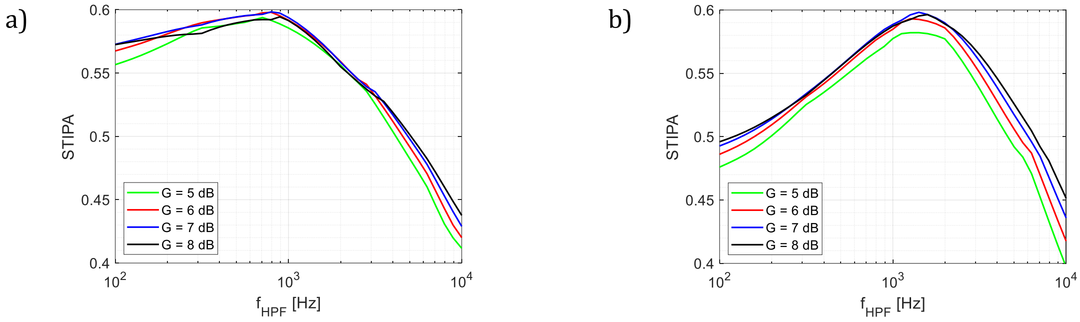

Figure 7. Effect of first-order filter cutoff frequency on STIPA for selected gains, for: T = 0.6 s, $L_{\mathrm{Aeq},s}$ = 70 dB, and interfering noise with $L_{\mathrm{Aeq},n}$ = 64 dB and the spectrum of: a) male speech, b) pink noise.

5. Conclusions

As shown in the paper, highpass filtering can significantly increase the speech transmission index provided by a sound system. The impact of highpass filtering is mainly determined by the interfering noise spectrum. In this paper, two cases considered by the author to be extreme were analysed, the signal spectrum of male speech and pink noise. For male noise, the effect of highpass filtering for large values of reverberation time and signal-to-noise ratio can be practically negligible. Highpass filtering in typical cases should provide larger STIPA values for the pink noise. It is best to use first-order filters to shape the signal spectrum using highpass filtering. However, it is not possible to unambiguously say what the filter cutoff frequency should be. This frequency is primarily determined by the interfering noise spectrum. Analysis shows that this frequency lies in the range of 400 - 2000 Hz. The use of highpass filtering with cutoff frequencies in the range of 250-300 Hz to protect the loudspeakers, in typical cases, can further increase STIPA.

Highpass filtering is a very simple technique for increasing speech intelligibility. However, the influence of individual frequency bands on speech intelligibility is quite complex. Further research are planned to speech intelligibility enhancement in sound systems using more advanced optimisation and equalization methods.

Additional information

The author declares: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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