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Optimizing the Comb Filters for Spectral Splitting of Speech to Reduce the Effect of Spectral Masking

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***Abstract*— Sensorineural hearing impairment is associated with widening of auditory filters, resulting in poor frequency selectivity with an increased susceptibility to masking. Earlier studies have shown that binaural dichotic presentation, using critical bandwidth based spectral splitting with perceptually balanced comb filters, helps in reducing the effect of spectral masking for persons with moderate bilateral sensorineural hearing impairment. In spectral splitting, the speech signal is filtered using a pair of linear phase FIR comb filters with complementary magnitude responses for binaural dichotic presentation. The objective of the present study is to optimize the comb filters with respect to the number of bands and bandwidth. Three different pairs of comb filters are investigated: constant bandwidth filters, critical band based filters, and 1/3 octave bandwidth filters. Evaluation of spectral splitting schemes, using these filters, through listening tests, indicate that 1/3 octave band and critical band based filters are superior to constant bandwidth filters.**

***Index Terms*— Sensorineural hearing loss, Spectral masking, Spectral splitting, Comb filters, Binaural dichotic presentation.**

I. INTRODUCTION

In cases of sensorineural hearing loss, the auditory filter bandwidth generally increases and frequency selectivity gets reduced due to increased masking [1] - [4]. Broader auditory filters result in perceptual smearing of spectral peaks and valleys. The spectral features that are not prominent may be smeared to the extent that they become imperceptible [3]. Earlier investigations [5]-[10] of splitting the speech into different bands and presenting the alternate bands to each ear was shown to be beneficial for people with moderate bilateral sensorineural hearing impairment, with residual hearing in both ears.

The comb filters used by Lyregaard [9] and Lunner [10], for spectral splitting of speech, were based on constant bandwidth, and filter structures were selected for efficient implementation. The magnitude responses do not show a clear demarcation of pass bands and stop bands, and gain variations at inter-band crossovers may not result in perceptual balance. The

investigations reported in [5], [7], [8] were based on auditory critical bands (CB) [1], [2], [11] specifically designed for separation of pass band and stop bands. Investigations using these filters showed an improvement in the speech perception capabilities of persons with sensorineural hearing loss, with residual hearing in both ears. The filters used by Chaudhari and Pandey [5] were designed for relatively flat pass band response, high stop band attenuation, and sharp transition band. Listening tests, conducted on moderate bilateral sensorineural hearing-impaired subjects, showed significant improvement in the recognition scores and perception of consonantal features.

Jangamashetti and Pandey [6] evaluated three schemes for dichotic presentation: spectral, temporal, and combined splitting of speech signal to reduce the effect of temporal and spectral masking. It was reported that the effectiveness of these schemes depends upon the type of individual's hearing loss. Temporal splitting was found to be effective for persons with high frequency hearing loss. For low frequency hearing loss, combined splitting scheme was found to be beneficial.

Cheeran and Pandey [7] evaluated the scheme of spectral splitting for binaural dichotic presentation to reduce the effect of spectral masking. Two perceptually balanced comb filters designed for minimum spectral distortion, based on auditory critical band, were used for spectral splitting. These filters were designed for transition width of 78-117 Hz, pass band ripple of less than 1 dB, stop band attenuation greater than 30 dB, and inter-band crossover gain adjusted within 4 to 6 dB of the pass band gain.

Listening tests were conducted, with 12 perceptually balanced VCV syllables, on normal subjects with simulated hearing loss and on subjects with moderate bilateral sensorineural hearing impairment. These tests showed an SNR advantage of 5 dB for normal hearing subjects under simulated hearing loss. For subjects with moderate bilateral

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sensorineural hearing loss, there was a significant improvement in recognition scores in the range of 21-29 %.

The emphasis of the investigations by Cheeran and Pandey [7] was on perceptual balance in spectral splitting for binaural dichotic presentation. The issue of optimization of comb filter bandwidth was not addressed in their study. The objective of the investigation, presented in this paper, is to study the effect of bandwidth in the comb filter for binaural dichotic presentation. Three different pairs of linear phase FIR filters, with complementary magnitude responses, were designed. First pair of filters considered is constant bandwidth comb filters with number of bands varying from two to eighteen. Second pair of comb filters was based on auditory critical bands (CB) as listed in Table 1. At lower frequencies, the bandwidths are nearly constant (approximately 100 Hz) and become nearly proportional to the center frequency at higher end. The third pair of comb filters was 1/3 octave bandwidth filters: with 70 Hz to 5 kHz divided into 19 bands of 1/3 octave bandwidth as listed in Table 2.

II. METHODOLOGY

A. Signal Processing

As shown in Fig.1, input signal is processed using a pair of comb filters, to get two outputs to be presented to the left and right ears through a pair of headphones for binaural dichotic presentation. Pair of linear phase FIR comb filters (512 coefficients), with complementary magnitude responses, were designed using frequency-sampling technique [12], [13]. The filters designed have pass band ripple of less than 1 dB. Minimum stop band attenuation is 64 dB for constant bandwidth filters, 29 dB for CB based comb filters, and 22 dB for 1/3-octave band filters. Inter-band crossover gain ranged between -5 to -6 dB. The magnitude response of pair of comb filters for three different bandwidths are shown in Fig. 2. It can be seen that for 1/3 octave filters, the bands at lower frequencies are very narrow while at high frequencies they are very wide. The CB based filter response approximates constant bandwidth response at lower frequency end and 1/3 octave response at higher frequency end. Fig. 3 shows the narrow band spectrograms of broad band noise, processed using filters with different bandwidths. These spectrograms show that the signal presented to two ears have complementary bands with minimal inter-band overlap.

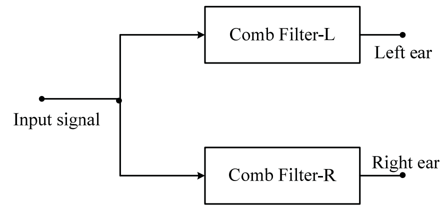


Fig. 1 Block diagram of spectral splitting using comb filters

B. Listening Test

Investigations were carried out using synthesized waveforms and recorded speech signals with a sampling rate of 10 k sa/s and 16-bit quantization. Listening tests were conducted on normal hearing subjects.

TABLE 1

LIST OF CRITICAL BANDS ALONG WITH THEIR CENTER FREQUENCIES [11]

Critical band	Center frequency in kHz	Frequency range in kHz
1	0.13	0.01 – 0.20
2	0.25	0.20 – 0.30
3	0.35	0.30 – 0.40
4	0.45	0.40 – 0.51
5	0.57	0.51 – 0.63
6	0.70	0.63 – 0.77
7	0.84	0.77 – 0.92
8	1.00	0.92 – 1.08
9	1.17	1.08 – 1.27
10	1.37	1.27 – 1.48
11	1.60	1.48 – 1.72
12	1.86	1.72 – 2.00
13	2.16	2.00 – 2.32
14	2.51	2.32 – 2.70
15	2.92	2.70 – 3.15
16	3.42	3.15 – 3.70
17	4.05	3.70 – 4.40
18	4.70	4.40 – 5.00

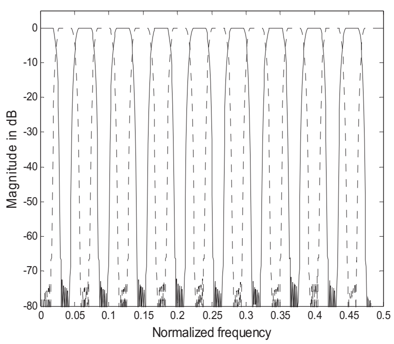
TABLE 2

1/3 OCTAVE BANDS

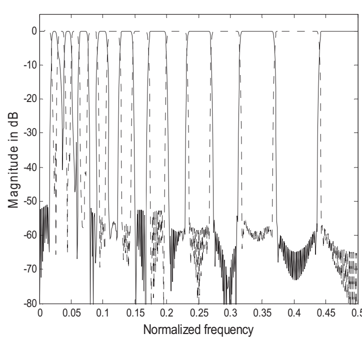
Band no.	Pass band (kHz)
1	0.0708-0.089
2	0.089 – 0.112
3	0.112 – 0.141
4	0.141 – 0.178
5	0.178 – 0.224
6	0.224 – 0.282
7	0.282 - 0.355
8	0.355 – 0.447
9	0.447 – 0.562
10	0.562 – 0.708
11	0.708 – 0.891
12	0.891 – 1.120
13	1.120 – 1.410
14	1.410 – 1.780
15	1.780 – 2.240
16	2.240 – 2.820
17	2.820 – 3.550
18	3.550 – 4.470
19	4.470 – 5.000

In the first experiment, we investigated the perceptual balance when the signal is switched between the two ears for all the three types of filters. Three linearly swept sinusoids were processed. First one was a sine wave whose frequency is slowly swept from 50 Hz to 5000 Hz, over 40 s duration. To study the perceptual balance separately at low and high frequencies, two more sine waves whose frequency is swept from 100 Hz to 300 Hz and from 3 kHz to 3.5 kHz respectively over 30 s duration were used. Six normal-hearing subjects participated in the experiment. Subjects were asked to observe the change in the perceived loudness when the signal switches between the two ears due to change in its frequency.

(a) Trans. b.w: 75-80 Hz no.of bands:18 crossover gain: -5 to -6 dB



(b) Trans. b. w: 45-55 Hz no.of bands: 18 cross



(c) Trans. b. w: 75-80 Hz no.of bands: 19 crossover gain: -5 to -6.4 dB

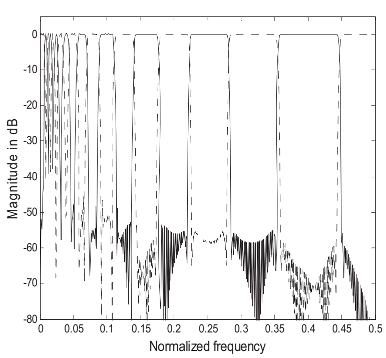


Fig. 2 Overlapped magnitude response of comb filter pairs: (a) constant bandwidth (b) CB based (c) 1/3 octave based.

The objective of the second experiment was to asses the perceived loudness in the two ears, which could result in lateralization of sound to one ear, in binaural dichotic presentation. The stimuli used in this experiment included vowels /*a i u*/, and a sentence "*we were away a year ago*". Same set of subjects as in Exp.I participated in this experiment also. Subjects were asked to rate the perceived loudness, of each binaurally presented stimulus, in the 0-10 range for each ear, with the total for the two ears being 10.

The third experiment was carried out to asses the perceived distortion for the three pairs of filters, with the same test material as in the second experiment. To study the effectiveness of these schemes in understanding the speech in the presence of noise, listening tests were also conducted by adding broad band noise (keeping constant SNR on short time i.e. 10 ms basis) to the unprocessed and processed speech signal. Noise was added at SNR values of 6, 3, 0, -3, -6, -9, -12, and -15 dB.

III. RESULTS

Listening tests in Exp. I, with swept sinusoids, did not indicate any change in the perceived loudness during the transfer of tones from one ear to another, showing that dichotic processing resulted in perceptually balanced outputs for all the three types of filters.

The second experiment was carried out to check any possible lateralization due to dichotic presentation. Table.3 shows the perceived loudness (on the scale 0 to 10, with 0 representing zero intensity and 10 representing maximum intensity) in each ear for different number of bands and for different speech signals. For small number of bands, the perceived loudness in one of the ears tends to dominate over the other. As seen in Table 3, the subjects perceived the same loudness in both the ears when the number of bands in the constant bandwidth filters was 16 or higher. No laterization was observed in case of CB and 1/3 octave based filters.

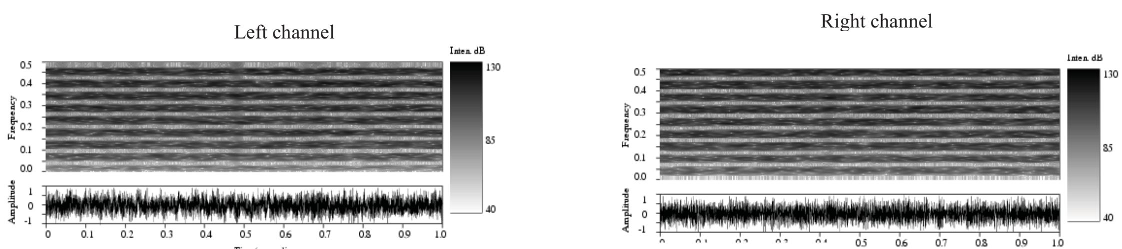
In the third experiment, the subjects did not perceive any distortion for the speech signals processed with CB based and 1/3 octave filters, indicating integration of dichotically processed speech. A small distortion was perceived for constant bandwidth based filters. Listening tests conducted by adding noise at various SNR values indicated that, the intelligibility of the processed speech was better than the unprocessed speech for same SNR, for all the three filters. The intelligibility of the processed speech in presence of noise was equally good for CB based and 1/3 octave band based filters and was relatively better than constant bandwidth filters for the same SNR.

TABLE.3
PERCEIVED RELATIVE LOUDNESS IN THE TWO EARS

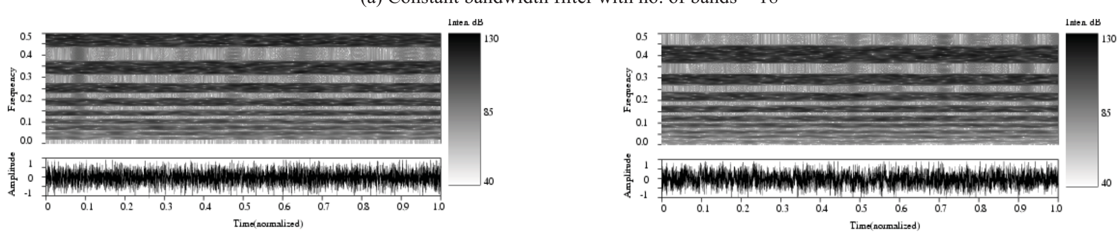
No. of bands	Chan-nel	Speech material			
		/a/	/i/	/u/	Sentence
2	Left	10	9	10	10
	Right	0	1	0	0
4	Left	9	10	10	9
	Right	1	0	0	1
6	Left	7	10	10	8
	Right	3	0	0	2
8	Left	7	8	8	6.5
	Right	3	2	2	3.5
10	Left	6.5	7	6.5	6.0
	Right	3.5	3	3.5	4.0
12	Left	6	7	6	5.5
	Right	4	3	4	4.5
14	Left	6	6	5.5	5.5
	Right	4	4	4.5	4.5
16	Left	5	5	5	5
	Right	5	5	5	5
18	Left	5	5	5	5
	Right	5	5	5	5

IV. CONCLUSIONS

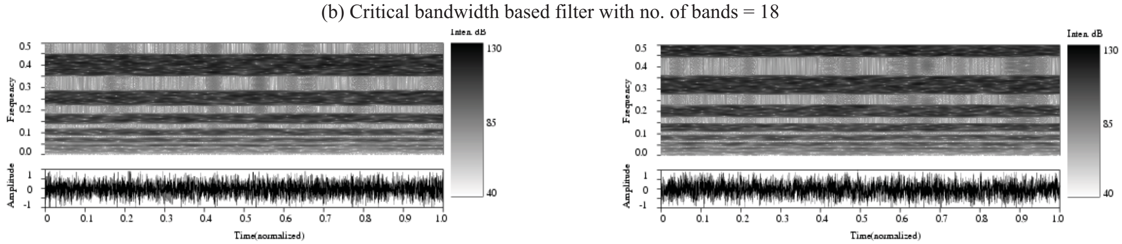
Binaural dichotic presentation, by using a pair of perceptually balanced comb filters with complementary magnitude responses, has earlier been shown to reduce the effect of spectral masking for persons with moderate bilateral sensorineural hearing loss. Here we have investigated the use of three different types of bandwidths in the comb filter magnitude response: constant bandwidth filters with number of bands varying from 2 to 20, critical band based comb filters and 1/3 octave bandwidth filters. In case of constant bandwidth filters, comb filters designed with up to 14 bands resulted in laterization of sounds presented. Constant bandwidth filters with 16 or more bands, CB based filters, and 1/3 octave bandwidth based filters did not show this problem. In the presence of noise, all the three types of filters improved speech intelligibility. Improvements because of CB based and 1/3 octave band based filters were similar for the same SNR, and better than constant bandwidth filters.



(a) Constant bandwidth filter with no. of bands = 18



(b) Critical bandwidth based filter with no. of bands = 18



(c) 1/3 octave bandwidth based comb filter with no. of bands = 19

Fig. 3 Narrow band spectrograms of broadband noise (500 ms, 10 k samples/s) processed using different pairs of comb filters

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