Fast Time-Scale Modification of Speech Using Nonlinear Clipping Methods

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<Abstract>

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Among the conventional time-scale modification (TSM) methods, the synchronized overlap and add (SOLA) method is widely used due to its good performance relative to computational complexity. But the SOLA method remains complex due to its synchronization procedure using the normalized cross-correlation function. In this paper, we introduce a computationally efficient SOLA method utilizing 3 level center clipping method, as well as zero-crossing and level-crossing information. The result of subjective preference test indicates that the proposed method can reduce the computational complexity by over 80% compared with the conventional SOLA method without serious degradation of synthesized speech quality.

* Keywords: Time-scale modification, Nonlinear spectral flattening, Zero-crossing, Level-crossing, 3 level center clipping, Computational efficiency.

1. INTRODUCTION

The purpose of time-scale modification (TSM) is to change the rate of speech while preserving other characteristics of original speech, such as formant structure, pitch periods, etc. There are various applications of time-scale modification. While there are a variety of techniques for the time-scale modification of speech [1]-[6], the synchronized overlap and add (SOLA) method is popular [4][5] because of its relatively good quality and simplicity. But the SOLA method still requires much computation in the normalized cross-correlation estimation in its synchronization procedure prior to the overlap and adding step[8][10][11]. Recently the methodology, that can reduce the computational complexity of an algorithm while preserving its output quality, has been emphasized with the need of embedded applications. Generally, embedded applications require the computational simplicity to obtain power consumption efficiency with limited battery capacity. In this paper, we propose a computationally efficient TSM method based on SOLA. The 3 level center clipping, zero crossing and level crossing method are employed in order to modify the normalized cross-correlation procedure of the conventional SOLA method. 3 level center clipping is a popular time-domain spectral flattening method for quasi-periodic signals [9]. Using this method, the signal spectrum can be flattened out, thereby reducing the computational complexity required for the normalization procedure in the conventional SOLA method. Generally, zero-crossing or level-crossing points contains more information for the frame synchronization than any other sample point in the case of quasi-periodic signals [7][9]. Therefore, the search space of the frame synchronization procedure in the conventional SOLA method can be reduced if the cross-correlation between two frames is estimated on zero-crossing or level-crossing points.

A series of computational complexity tests using the proposed method showed that the original computational complexity can be reduced by over 80% compared with the conventional SOLA method. This paper compares the proposed method with the global and local search TSM (GLS-TSM) method [7] which is one of the computationally efficient TSM methods based on the SOLA method. A subjective preference test by human listeners was conducted. The result of which indicates that the performance of the proposed method is close to that of the conventional SOLA method and superior to that of the GLS-TSM method while providing tremendously reduced computational complexity.

This paper is organized as follows. After a brief review of the conventional SOLA method and the GLS-TSM method in Section 2, the proposed method and the performance evaluation are described in Section 3, and experiment results are presented in Section 4. Conclusions follow in Section 5.

2. REVIEW OF CONVENTIONAL TIME-SCALE MODIFICATION METHODS

2.1. Synchronized Overlap and Add (SOLA) method

The key idea of the SOLA method is to shift and average the overlapping frames of a signal in a synchronized fashion at the points of highest cross-correlation[4][5]. As a result, the time-scale modified signal by the SOLA method preserves the time-dependent pitch, the spectral magnitude and phase to a large degree to produce relatively high quality speech. Let $x(n)$ be the input signal and $y(n)$ the time-scale modified signal. Given the frame length of N, we introduce the analysis inter-frame interval S_a, and the synthesis inter-frame interval S_s. Then the ratio of S_s/S_a is the modification factor α. $\alpha > 1$ corresponds to time expansion and $\alpha < 1$ corresponds to compression. The SOLA method begins with copying the first frame of size N from $x(n)$ to $y(n)$. Then the m-th frame of the input signal $x(mS_a+j)$, $0 \le j \le N-1$, is synchronized and averaged with a neighborhood of $y(mS_s+j)$ on a frame-by-frame basis. The synchronization point is determined by maximizing the normalized cross-correlation between $x(mS_a+j)$ and $y(mS_s+j)$ as follows:

$$R_m(k)= \frac{\sum_{j=0}^{L-1} y(mS_s+k+j)x(mS_a+j)}{\left[\sum_{j=0}^{L-1} y^2(mS_s+k+j)\sum_{j=0}^{L-1} x^2(mS_a+j)\right]^{1/2}}, \quad -\frac{N}{2} \le k \le \frac{N}{2} \tag{1}$$

where L is the length of overlap between $x(mS_a+j)$ and $y(mS_s+j)$. Once the synchronization point $k_m = \arg max\{R_m(k)\}$ is found, the time-scale modified signal $y(n)$ is updated as follows:

$$y(mS_s+k_m+j)= (1-f(j))y(mS_s+k_m+j)+f(j)x(mS_a+j), \quad 0 \le j \le L_m-1 \tag{2}$$

where L_m is the range of overlap of the two signals for the particular k_m involved and $f(j)$ is a weighting function such that $0 \le f(j) \le 1$. A raised cosine weighting function and a linear weighting function are evaluated but the performance difference between them is not distinguishable in 8 kHz sampled speech signal. In this paper, we used a linear weighting function of $f(j) = j/(L_m - 1)$. Although the SOLA method produces a relatively fine quality of speech, equation (1) still requires much computational complexity.

2.2. Global and Local Search TSM (GLS-TSM)

The GLS-TSM [7] method is based on the SOLA method. But the GLS-TSM method uses zero-crossing rate and characteristic vectors instead of the normalized cross-correlation function in order to evaluate the global and local similarity between the synthesized speech frame and the analyzed speech frame in the synchronization procedure. To do so, the GLS-TSM method can reduce much computational complexity compared with the conventional SOLA method. The GLS-TSM method uses zero-crossing rate in order to evaluate global similarity. The global similarity matched sample point k_{global} is found when the difference of the zero-crossing rates between two adjacent frames is minimized. Local similarity is evaluated with the characteristic vector on the basis of the k_{global} sample point and the local similarity evaluation is performed on the zero-crossing point. Consequently those characteristic vectors are calculated on the zero-crossing points. The characteristic vector f used in the local similarity evaluation procedure is as follows:

$$
\begin{aligned}
&f_1 \quad x(i) - x(i+1) \\
&f_2 \quad |x(i)| \\
&f_3 \quad |x(i+1)| \\
&f_4 \quad \{x(i) - x(i+2)\}/2 \\
&f_5 \quad |x(i+2)| \\
&f_6 \quad \{x(i) - x(i+3)\}/3 \\
&f_7 \quad |x(i+3)| \\
&f_8 \quad \{x(i-1) - x(i+1)\}/2 \\
&f_9 \quad |x(i-1)| \\
&f_{10} \quad \{x(i-2) - x(i+1)\}/3 \\
&f_{11} \quad |x(i-2)|
\end{aligned} \tag{3}
$$

The distance measure for the local similarity evaluation procedure is as follows:

$$d_{k,i} = \frac{1}{11}\sum_{j=1}^{11}|f_x(j) - f_{y,i}(j)| \tag{4}$$

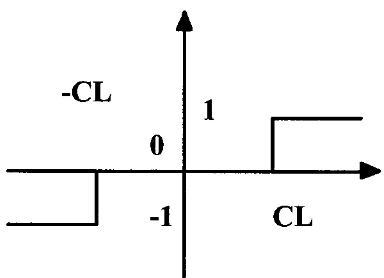
where k is the first zero-crossing point of speech signal $x(n)$. $f_x(j)$ is the j-th element of the characteristic vector on a zero-crossing point of speech signal $x(n)$. $f_{y,i}(j)$ is the j-th element of the characteristic vector on the i-th zero-crossing point of speech signal $y(n)$. The GLS-TSM method requires only a small amount of computation compared with the conventional SOLA method, but as such, the quality of the synthesized speech suffers in comparison with that offered by the conventional SOLA method.

3. TIME-SCALE MODIFICATION OF SPEECH USING NONLINEAR CLIPPING METHODS

3.1. The Computationally Efficient SOLA Method 1 (CE-SOLA 1)

In order to reduce the computational complexity of the conventional SOLA method, 3 level center clipping and zero-crossing methods are applied in the conventional synchronization procedure.

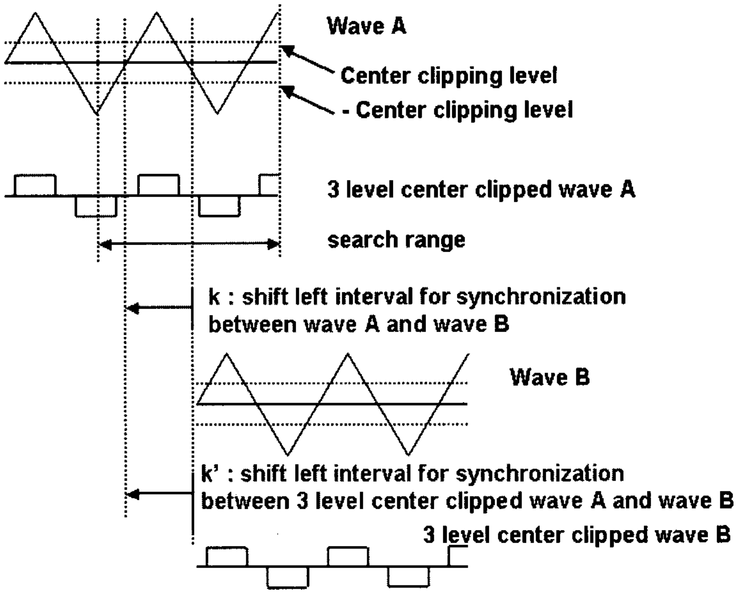
The 3 level center clipping method is popular for nonlinear spectral flattening purpose[9]. The normalization step of the conventional SOLA method can be omitted by taking the advantage of the spectral flattening property. 3 level center clipped input samples can have one of three values: -1, 0 or 1.



<Figure 1> 3-level center clipping function

<Figure 1> shows the 3-level center clipping function. The vertical axis plots the clipping level and the horizontal axis plots the magnitude of signal. The CL indicates

the center-clipping level. For a speech signal segment, the maximum amplitude, $A_{\max}$ is found and the clipping level, CL, is set equal to a fixed percentage of $A_{\max}$ [9].



<Figure 2> Example of 3-level center clipped signal in the frame synchronization procedure

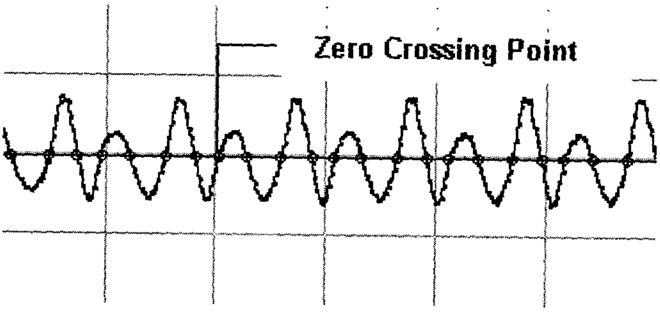
<Figure 2> shows that 3-level center clipped signal can play an important role in the frame synchronization procedure. The number of search points in the synchronization step of the conventional SOLA method can be reduced by evaluating the waveform similarity using zero-crossing points. Zero-crossing points are detected as follows:

$$Z(n)= \frac{|sgn\{x(n)\}- sgn\{x(n-1)\}|}{2} \tag{5}$$

$where$

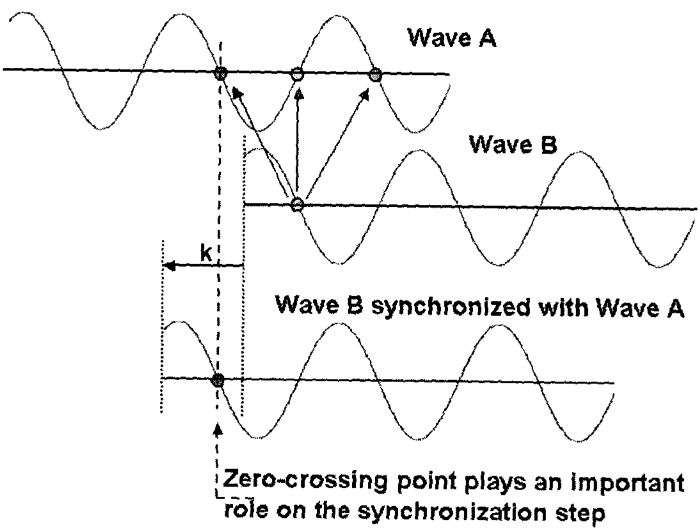
$$sgn\{x(n)\}= \begin{cases} +1, & x(n)\geq 0 \\ -1, & x(n)< 0 \end{cases}$$

If $Z(n)$ is equal to 1, then the point n indicates the zero-crossing point.



<Figure 3> Example of zero-crossing points in a speech signal

<Figure 3> shows an example of zero-crossing points in a speech signal.



<Figure 4> Importance of zero-crossing points

<Figure 4> shows that zero-crossing points are important to the frame synchronization procedure with regard to the periodic signals. This concept can be extended in the case of quasi-periodic signals such as speech.

The modified cross-correlation function used in the synchronization procedure of the proposed method is as follows:

$$\widehat{R_m}(k_{zc}) = \frac{\sum_{j=0}^{L-1} \hat{y}(mS_s + k_{zc} - k_{fz} + j)\hat{x}(mS_a + j)}{L}, \quad k_{\min} \le k_{zc} \le k_{\max} \tag{6}$$

where,

$\hat{y}$: 3-level center clipped synthesized speech signal

$\hat{x}$: 3-level center clipped analyzed speech signal

k_{zc}: zero-crossing point of $y(n)$

k_{fz}: first zero-crossing point of $x(n)$

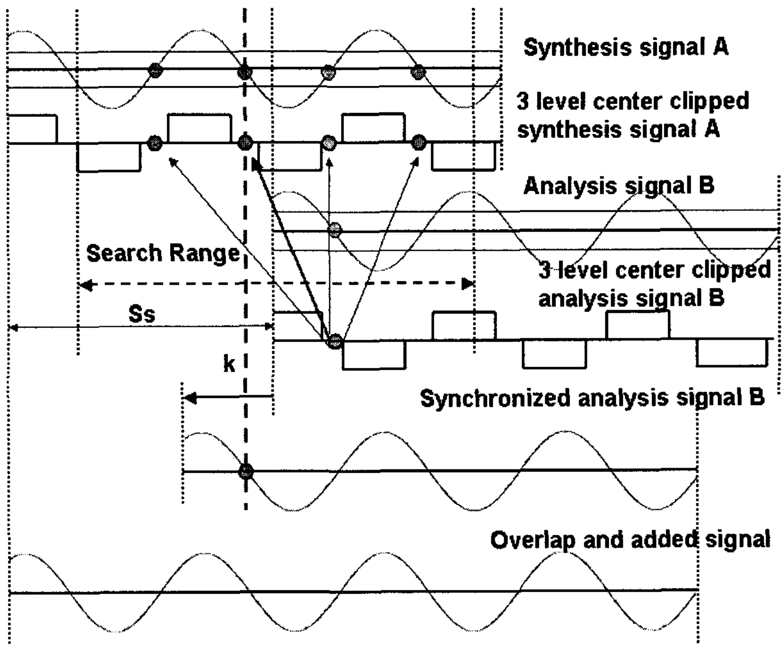
The search range for the waveform similarity evaluation is from k_{min} to k_{max}. As shown in the equation (6), the modified cross-correlations are estimated not at all the sample points within the search range but at the zero-crossing points only. Therefore, the search space in the synchronization procedure can be reduced. In the case of CE-SOLA 1, the equation (6) is applied to all input frames for the synchronization procedure.

<Figure 5> shows the synchronization procedure of the proposed CE-SOLA 1 using 3-level center clipped signal and zero-crossing points in the case of periodic signals. As shown, the synchronization procedure is conducted by comparing the 3-level center clipped synthesis signal and analysis signal at the zero-crossing points. The thick arrow indicates the synchronization point.

3.2. The Computationally Efficient SOLA Method 2 (CE-SOLA 2)

Generally, background silence or unvoiced speech frames may have too many zero-crossing points. Therefore, the zero-crossing rate is high in the silence or unvoiced speech frames. Zero-crossing rate is estimated as follows:

$$Zr = \frac{1}{L}\sum_{n=0}^{L-1} Z(n) = \frac{1}{L}\sum_{n=0}^{L-1} \frac{|sgn\{x(n)\} - sgn\{x(n)\}|}{2} \tag{7}$$



<Figure 5> Example of synchronization procedure of CE-SOLA 1

In these cases, computational efficiency requires that the search space of the synchronization procedure be reduced. We estimate the frame similarity with a certain interval in the case of the high zero-crossing rate frame, find the global synchronization point and then, estimate the local similarity among the points adjacent to the global synchronization point. The modified cross-correlation equation for this purpose is as follows:

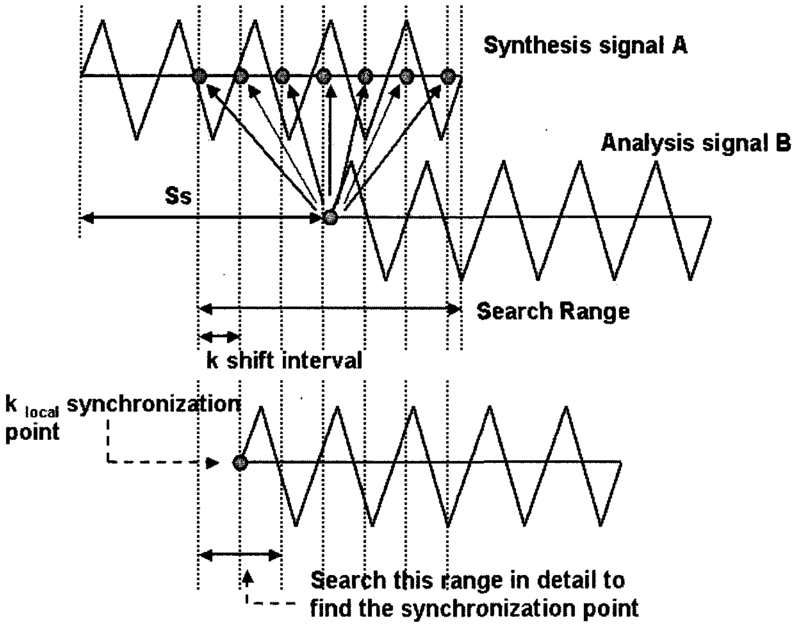
$$\widehat{R_m}(k_{shift}) = \frac{\sum_{j=0}^{L-1} \hat{y}(mS_s + k_{shift} + j)\hat{x}(mS_a + j)}{L}, \tag{8}$$

$$k_{shift} = k_{\min}, k_{\min} + s, k_{\min} + 2s, \ldots, k_{\min} + \max shift \times s$$

$$\max shift \le floor\left(\frac{k_{\max} - k_{\min}}{s}\right)$$

s: positive integer

In the case of the CE-SOLA 2, the equation (8) is applied to high zero-crossing rate frames such as silence or unvoiced speech frames in the synchronization procedure.



<Figure 6> Example of synchronization procedure of the CE-SOLA 2 in case of frames with high zero-crossing rate

<Figure 6> shows an example of the CE-SOLA 2 in the case of high zero-crossing rate frames such as silence or unvoiced speech frames in the synchronization procedure. As shown, the local synchronization point can be found throughout the sparse search procedure and the global synchronization point is obtained by searching the points adjacent to the local synchronization point.

3.3. The Computationally Efficient SOLA Method 3 (CE-SOLA 3)

In order to reduce the computational complexity of the conventional SOLA method more efficiently, the level-crossing method is introduced in place of the zero-crossing method in the waveform similarity estimation step.

Level-crossing points are detected as follows:

$$Z(n) = \frac{|lvl\{x(n)\} - lvlx(n)|}{2} \quad (9)$$

$$where$$

$$lvlx(n) = \begin{cases} +1, & x(n) \geq CL \\ 0, & -CL \leq x(n) < CL \\ -1, & x(n) < -CL \end{cases}$$

where CL indicates the center clipping level. If $Z(n)$ is not equal to 0, then the point n indicates the level-crossing point. The advantage of the level-crossing method is that the number of zero-crossing points can be controlled by the center clipping level. Thereby, the computational complexity of the CE-SOLA 3 can be adjusted. The modified cross-correlation equation for the synchronization step is as follows:

$$\widehat{R_m}(k_{lc}) = \frac{\sum_{j=0}^{L-1} \hat{y}(mS_s + k_{lc} - k_{fl} + j)\hat{x}(mS_a + j)}{L}, \quad k_{min} \le k_{lc} \le k_{max} \qquad (10)$$

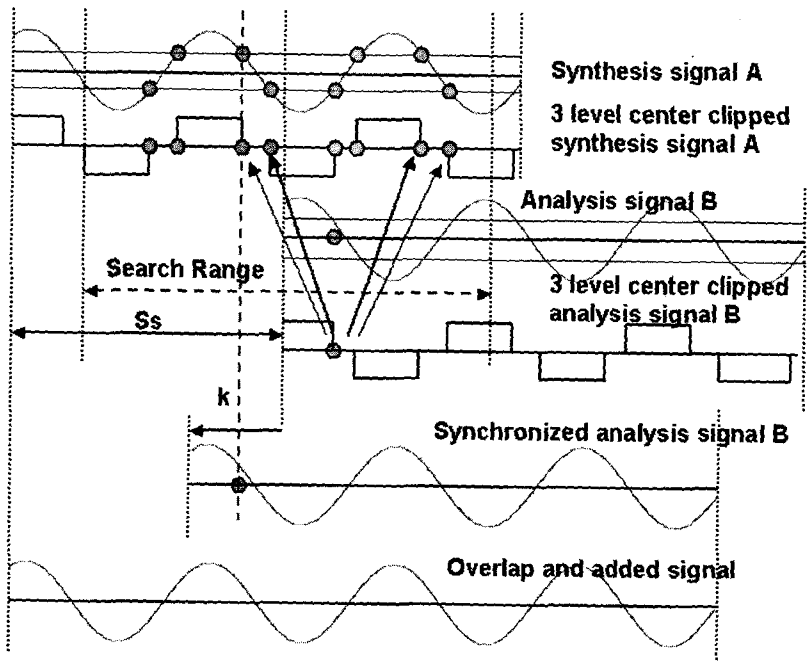
where,

$\hat{y}$: 3-level center clipped synthesized speech signal

$\hat{x}$: 3-level center clipped analyzed speech signal

k_{lc}: level-crossing point of $y(n)$

k_{fl}: first level-crossing point of $x(n)$



<Figure 7> Example of synchronization procedure of the CE-SOLA 3 in case of frames with high zero-crossing rate

The computational complexity of CE-SOLA 3 is reduced as the center clipping level of speech is increased, because the search space required for the waveform similarity evaluation procedure is compressed.

<Figure 7> shows the synchronization procedure of the proposed CE-SOLA 3 using 3-level center-clipped signal and level-crossing points in the case of periodic signals. The synchronization point can be obtained by comparing the 3 level center clipped synthesis and the analysis signal at the level-crossing points. Positive-going and negative-going level-crossing points are considered to effect a greater reduction in the computational complexity, in that the waveform similarity is tested at the level-crossing points with the same polarity.

4. Experimental Results

A series of computational complexity evaluation tests were performed. The ETRI post name and Korean news speech database were used for the tests. The speech signal was down-sampled to 8 kHz. The frame size and analysis inter-frame interval Sa were chosen to be 30 ms and 10 ms, respectively, and the TSM rate of 0.5 was applied. The clipping level CL was set equal to 50% of the maximum amplitude for the given speech signal frame in the case of CE-SOLA 1, 2 and 3. A zero-crossing ratio threshold equal to 0.3 was set to detect a high zero-crossing rate frame in the case of CE-SOLA2. The maximum amplitude was found in the first and last 10 ms samples of the given speech signal frame. The average number of sample points per frame, at which normalized or modified cross-correlation was estimated, was compared.

In <table 1>, each waveform similarity estimation frequency is the average number of points normalized by the result of the conventional SOLA method. A high waveform similarity estimation frequency indicates that more waveform similarity tests are required for the synchronization step. A low waveform similarity estimation frequency indicates the opposite.

<Table 1> Comparison of estimation frequency of normalized/modified cross-correlation function

TSM method	Waveform similarity estimation frequency (%)
Conventional SOLA	100.00
CE-SOLA 1	13.21
CE-SOLA 2	11.92
CE-SOLA 3	1.46

The normalization step in the waveform synchronization is omitted in the proposed methods by taking advantage of nonlinear spectral flattering method, called 3-level center clipper. Thereby, the proposed methods can be more efficient than the conventional SOLA method in the cross-correlation calculation procedure. However, additional computational complexity is required to obtain 3-level center-clipped input samples, zero-crossing, and level-crossing information.

The results of computational complexity evaluations are shown in <table 2>. This test was conducted on a 486 100-MHz personal computer (PC) platform and the average processing time is measured throughout the Korean broadcast news speech database. The TSM rate 0.5 is applied to this experiment. The average time ratio is the percent value that each processing time is normalized by the processing time of the conventional SOLA method. The computational complexity of the proposed methods can be reduced by over 80% compared with the conventional SOLA method. Especially, the computational complexity of CE-SOLA 3 method is less than 10% of the conventional SOLA method.

<Table 2> Computational complexity comparison of several TSM methods

	SOLA	GLS-TSM	CE-SOLA1	CE-SOLA2	CE-SOLA3
Average time ratio	100%	16.2%	18.4%	16.6%	8.7%

In the aspects of speech quality, a series of preference tests by human listeners was conducted to evaluate the performance of the proposed methods. The speech materials used in this test consisted of five phonetically rich Korean sentences, each spoken by a different male speaker in a quiet environment. The speech data were sampled at 8 kHz sampling rate. The average pitch of the speech data was around 180 Hz and the pitch ranged from 80 Hz to 300 Hz. The window length, N, was 30 ms and the analysis inter-frame interval, S_a was 10 ms. The clipping level CL was set equal to 50% of the maximum amplitude for a given speech signal frame in the case of CE-SOLA 1, 2 and 3.

Three types of TSM methods were implemented for this test: SOLA, GLS-TSM and the computationally efficient SOLA methods 1, 2 and 3. A listener preference test was conducted with speech data for two different TSM factors: $\alpha = 0.7$ and $\alpha = 1.5$. The listeners consisted of 18 males and 2 females, ranging in age from 24 to 29. The listeners used headphones, taking the test individually with the experimenter to minimize distractions. All of the listeners were native Korean speakers and had no previous experience in this kind of listening preference test.

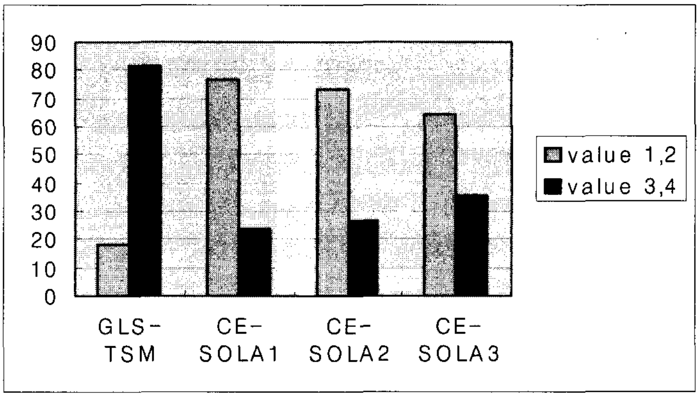
<Table 3> shows the valuation basis for the listeners.

<Table 3> The valuation basis

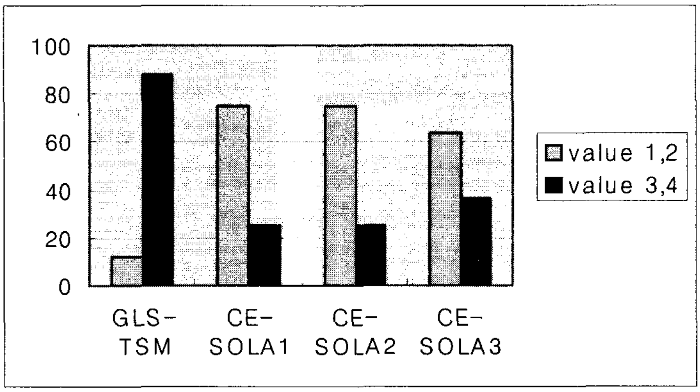
Valuation Basis	Contents
1	B is equal to A
2	B is almost same as A
3	Somewhat different (A is a little better than B)
4	Quite different (A is much better than B)

A: Conventional SOLA method

B: GLS-TSM. CE-SOLA 1. CE-SOLA2 or CE-SOLA 3



(a)

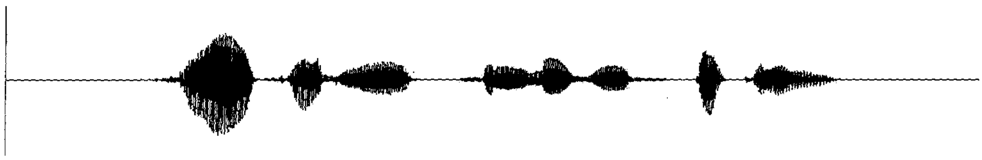


(b)

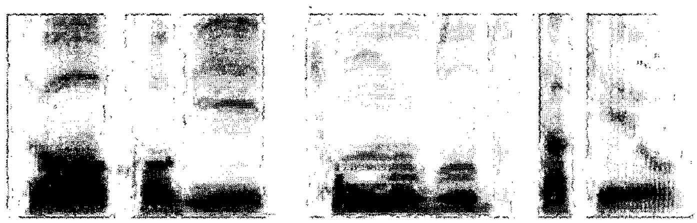
<Figure 8> The preference test results (a) $\alpha = 0.7$, (b) $\alpha = 1.5$.

The vertical axis in <Figure 8> indicates a percentage value of the evaluation count collected from the listeners. The preference test result shown in the figure indicates that the performance of the proposed methods is superior to GLS-TSM and similar to the conventional SOLA method.

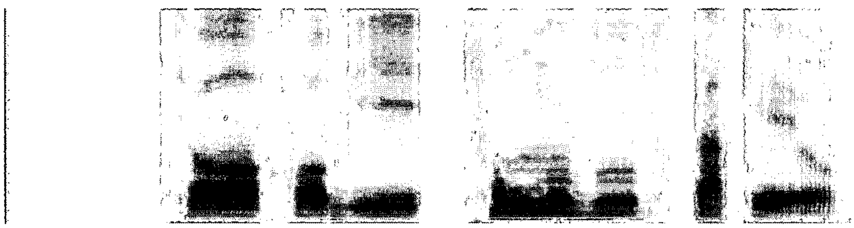
<Figure 9> shows that the spectrogram of the time-scale modified speech signal by the proposed method is similar to that of the conventional SOLA method, which indicates that the spectral characteristics of the time-scale modified speech by the proposed methods are maintained well.



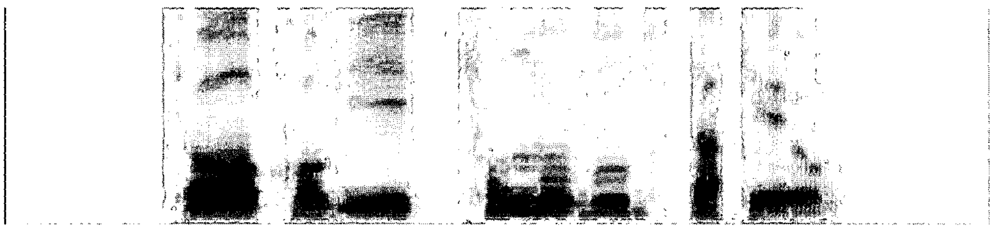
(a) The original speech waveform



(b) The spectrogram of time-scale modified speech by the conventional SOLA method



(c) The spectrogram of time-scale modified speech by the CE-SOLA 1 method



(d) The spectrogram of time-scale modified speech by the CE-SOLA 3 method

<Figure 9> Original waveform and spectrograms of time-scale modified speech signal ($\alpha = 0.7$)

The results of subjective preference listening test showed that the quality of the modified speech by the proposed methods is relatively similar with the cases of the conventional SOLA method. Obviously, the performance of CE-SOLA 3 is decreased with the increase of the center clipping level. However, the speech quality of the proposed method was nontheless acceptable in the case of a center clipping level corresponding to 90% of the maximum amplitude.

5. CONCLUSIONS

The proposed time-scale modification (TSM) methods take advantage of 3-level center clipping method, as well as the zero-crossing or level-crossing points of the speech signal in the synchronization procedure of the conventional SOLA method in order to reduce the computational complexity. With 3-level center clipping method, the normalization step of the normalized cross-correlation calculation in the conventional SOLA method is safely omitted. Therefore, the computational complexity of the normalization component is reduced and the overflow problem in the case of the real-time implementation based on a fixed-point DSP or microprocessor platform can be ignored. By evaluating the waveform similarity at the zero-crossing points or the level-crossing points only, the search space is reduced without serious performance degradation.

By the proposed methods, we can reduce the computational complexity of the overall TSM algorithm by over 80% compared with the conventional SOLA method. Particularly, computational complexity of the CE-SOLA 3 method is less than 10% of the conventional SOLA method. The subjective preference listening test result in the aspect of speech quality indicates that the proposed methods can produce a relatively good time-scale modified speech signal. As mentioned above, the CE-SOLA 3 method still entails a trade-off between computational complexity and performance with regard to the center clipping level, but the resulting performance degradation by increasing the center clipping level was not so significant. In general, zero-crossing locations are sensitive to DC offset and noise, level-crossing locations being less sensitive. DC offset can be removed with simple DC offset removal filter but noise can degrade the performance of the proposed method. Nontheless it is confirmed that in the case of speech signals of relatively high SNR (more than 15 dB), such as that of Korean broadcast news, the proposed method works well within the help of the 3-level center clipper.

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접수일자: 2006년 8월 10일
게재결정: 2006년 9월 23일

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