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FAST LSP CALCULATION AND QUANTIZATION WITH APPLICATION TO THE CELP FS1016 SPEECH CODER

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ABSTRACT

Line Spectrum Pair (LSP) representation is used for spectral quantization in the CELP FS1016 speech coder, where the LSPs are first calculated, and then quantized using 34-bit non-uniform scalar quantization. In the algorithm proposed in this paper, computational complexity is decreased by searching the zero-crossings on the grid formed by the values of the quantization tables. As the actual LSPs are not calculated, two criteria to select the "closest" quantized LSPs are proposed. These criteria take into account the interaction between successive LSPs. The efficiency and reliability of the proposed algorithm are improved using the interlacing property of the LSPs and knowledge of the direction of the sign-change at every zero-crossing. The proposed algorithm is compared with the existing Kabal's algorithm (followed by quantization), showing similar quantization performance. The computational complexity on a fixed-point DSP56001 implementation is reduced by 66 %, using the proposed algorithm.

1. INTRODUCTION

Line Spectrum Pair (LSP) representation of *10*-th order Linear Predictive Coding (LPC) parameters is widely used in narrowband speech coders, such as the FS1016 CELP coder [1]. The definition of LSP parameters, as well as an explanation of Kabal's efficient algorithm for computing the LSP parameters, are given in Section 2.

In the CELP FS1016, the LSPs are first calculated, and then quantized using 34-bit non-uniform scalar quantization [1]. The quantized LSPs that are closest to the actual LSPs are determined using an "horizontal-distance" criterion [2], which is explained in Section 3. In the fast direct conversion from LPC to quantized LSP proposed by Wolovitz [2] the zero-crossings are searched on a grid formed by the values of the quantization tables. As the actual LSPs are not known, the closest quantized LSPs are determined using a "vertical-distance" criterion (see § 3). This method is computationally more efficient than Kabal's algorithm followed by quantization, at the cost of degradation in the speech quality. In [2], it is suggested that the degradation in speech quality is due to the coarse grid used in the zero-crossing search. The use of two interpolated values between each quantized value is suggested to avoid missing zero-crossings [2], but this would greatly increase the computational complexity.

We have found that the degradation in quality is not due to missing zero-crossings, but to the criterion used for selecting the closest quantized LSP and to the fact that the interaction between successive LSPs is not taken into account. In Section 3, two selection criteria that improve the quality with a small increase in computational complexity are proposed. The interlacing property of the LSPs as well as knowledge of the direction of the sign-change at every zero-crossing are also used for improving efficiency and reliability of the proposed algorithm.

Experimental evaluation of this algorithm is shown in Section 4. The implementation of the proposed algorithm on a DSP56001 is explained in Section 5, where the complexity of this implementation is compared to Kabal's algorithm followed by quantization. Conclusions are given in Section 6.

2. LSP CALCULATION

The starting point for deriving the *10*-th order LSPs is the *10*-th order LPC analysis filter [3]:

$$A_{10}(z) = 1 + \sum_{k=1}^{10} a_k \cdot z^{-k} \tag{1}$$

The polynomials, $P'_{10}(z)$ and $Q'_{10}(z)$, are given by:

$$\begin{aligned} P_{10}(z) &= A_{10}(z) + z^{-11}A_{10}(z^{-1}) = (1+z^{-1})\cdot P'_{10}(z) \\ Q_{10}(z) &= A_{10}(z) - z^{-11}A_{10}(z^{-1}) = (1-z^{-1})\cdot Q'_{10}(z) \end{aligned} \tag{2}$$

The zeros of $P'_{10}(z)$ and $Q'_{10}(z)$ are on the unit circle and interlaced [3]. The angles of these zeros (upper semicircle of the z-plane) are the 10 LSP parameters, denoted as $\{\omega_i\}$.

A survey of existing algorithms for LSP calculation was done [5], and three algorithms that were found promising for efficient real-time implementation were selected and compared, from the point of view of accuracy, reliability and computational complexity. Kabal's algorithm [3] was found to be the most efficient and suitable for application in the CELP FS1016.

2.1. Kabal's Algorithm

In Kabal's algorithm [3], two 5-th order polynomials, $P'_{10}(x)$ and $Q'_{10}(x)$, are obtained by evaluating $P'_{10}(z)$ and $Q'_{10}(z)$ on the unit circle ($z = e^{j\omega}$), and using the mapping $x = \cos(\omega)$. The roots of $P'_{10}(x)$ and $Q'_{10}(x)$ are the LSPs in the "x-domain", denoted as $\{x_i\}$, with $x_i = \cos(\omega_i)$.

In the numerical solution proposed in [3], the zero-crossings are searched starting at $x = +1$, with decrements of $\Delta = 0.02$. Once a zero-crossing is found, its position is refined by four successive bisections and a final linear interpolation. The maximum number of polynomial evaluations is 150. An efficient recursion for polynomial evaluation, requiring only 4 multiplications and 9 additions, is also proposed in [3].

3. THE PROPOSED ALGORITHM

In the CELP FS1016, the LSPs are first calculated, and then quantized using a 34-bit non-uniform scalar quantization [1]. A different quantization table is used to quantize each of the 10 LSPs.

To speed up the calculation and quantization processes, a quantized-search technique is used, obtaining the algorithm referred to as "quantized-search Kabal". The quantized LSPs are denoted as $\{qx_i\}$, and the interlacing property, which is a necessary condition for stability of the synthesis filter upon quantization is given by:

$$+1 > qx_1 > qx_2 > \ldots > qx_{10} > -1 \tag{3}$$

To locate the quantized value (qx_i) of the *i*-th LSP (x_i), the corresponding zero-crossing of either $P'_{10}(x)$ or $Q'_{10}(x)$ is searched. This search uses the values of the *i*-th quantization table. Once the interval (ξ_{k-1},ξ_k) containing the zero-crossing is found (see Figure 1), first the quantized LSP is selected as ξ_k, and then its position is corrected using either the "single-correction" or the "coupled-correction" criterion, explained in the next sub-sections. Once a quantized LSP, qx_i, is determined, the search for the next quantized LSP, qx_{i+1}, is done using the values of the *i+1*-th quantization table, starting from the first "allowed" value that would ensure the ordering property of Equation (3).

As the direction of the sign-change at every zero-crossing is known [5], it is possible to detect if the zero-crossing has already occurred at the first allowed value, improving efficiency and reliability of the algorithm. If the zero-crossing has already occurred at the first allowed value, the "coupled-correction" criterion is used to correct the position of the quantized LSP. Otherwise, the "single-correction" criterion is used.

3.1. «Single-Correction»

The "single-correction" criterion is explained with the help of Figure 1. If the interval (ξ_{k-1},ξ_k) contains the *i*-th zero-crossing, $qx_i = \xi_k$ is selected. Then, if ξ_k is not the first allowed value of the quantization table, qx_i can be "single-corrected", choosing ξ_{k-1} if it is closer to x_i.

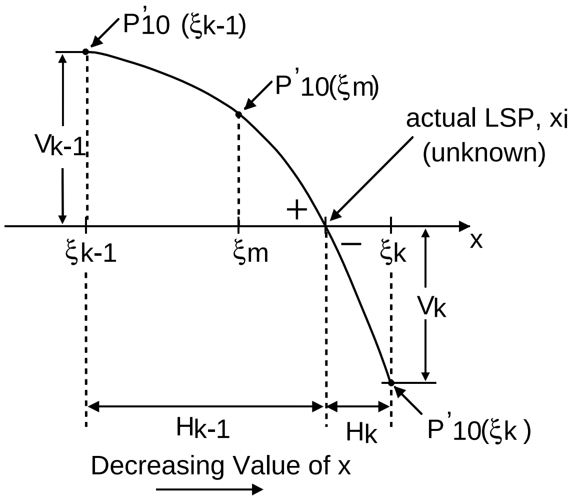

Figure 1: Illustration of a zero-crossing of the polynomial $P'_{10}(x)$ from positive to negative.

When the LSPs are first calculated and then quantized, x_i is known, and the following "horizontal single-correction" (H-SC) criterion is used [2]:

$$\begin{array}{ll} \text{if } H_k \geq H_{k-1} & \Rightarrow qx_i = \xi_{k-1} \\ \text{else} & \Rightarrow qx_i = \xi_k \end{array} \tag{4}$$

where H_{k-1} and H_k are the horizontal distances from ξ_{k-1} and ξ_k to the actual LSP value x_i, as shown in Figure 1.

In the case of a quantized domain search, only the values of $P'_{10}(\xi_{k-1})$ and $P'_{10}(\xi_k)$ are known, but not x_i. In the fast conversion from predictor coefficients to quantized LSPs proposed by Wolovitz [2], qx_i is selected using the "vertical single-correction" (V-SC) criterion:

$$\begin{array}{ll} \text{if } V_k \geq V_{k-1} & \Rightarrow qx_i = \xi_{k-1} \\ \text{else} & \Rightarrow qx_i = \xi_k \end{array} \tag{5}$$

where V_{k-1} and V_k are the vertical distances from $P'_{10}(\xi_{k-1})$ and $P'_{10}(\xi_k)$ to the x-axis, as shown in Figure 1. This V-SC criterion does not necessary choose the closest value to x_i, depending on the concavity of the polynomial $P'_{10}(x)$ or $Q'_{10}(x)$ at the zero-crossing. We propose the following criterion, which is equivalent to the H-SC criterion and can be used in a quantized domain search, at the cost of 10 extra polynomial evaluations. The polynomial $P'_{10}(x)$ is evaluated at the center of the interval containing the zero-crossing (ξ_m). If the zero-crossing is from positive to negative:

$$\begin{array}{ll} \text{if } P'_{10}(\xi_m) \leq 0 & \Rightarrow qx_i = \xi_{k-1} \\ \text{else} & \Rightarrow qx_i = \xi_k \end{array} \tag{6}$$

else, if the zero-crossing is from negative to positive:

$$\begin{array}{ll} \text{if } P'_{10}(\xi_m) \geq 0 & \Rightarrow qx_i = \xi_{k-1} \\ \text{else} & \Rightarrow qx_i = \xi_k\ . \end{array} \tag{7}$$

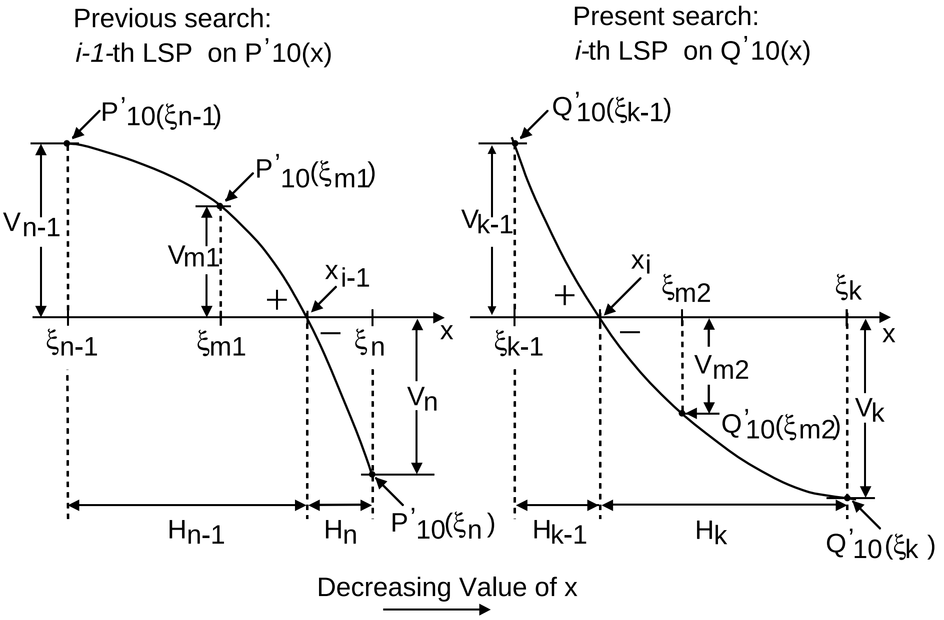

Figure 2: Illustration of two successive zero-crossings, from positive to negative, of the polynomials $P'_{10}(x)$ and $Q'_{10}(x)$.

3.2. «Coupled-Correction»

This criterion considers the interaction between two consecutive LSPs. In Figure 2, the interval (ξ_{n-1},ξ_n) contains the *i-1*-th LSP, x_{i-1}, and the interval (ξ_{k-1},ξ_k) contains the *i*-th LSP, x_i. In the previous search, as ξ_n is closer to x_{i-1} than ξ_{n-1}, $qx_{i-1}=\xi_n$ was selected (i.e., qx_{i-1} was not "single-corrected").

If ξ_k is the first allowed value of the *i*-th quantization table, then (ξ_{n-1},ξ_n) and (ξ_{k-1},ξ_k) overlap, with $\xi_{k-1} > \xi_n$, and the choice of $qx_{i-1} = \xi_n$ would force the choice $qx_i = \xi_k$, to preserve the interlacing property. In this case, the "coupled-correction" criterion is used to decide which choice is better:

$$(qx_{i-1},qx_i)=(\xi_n,\xi_k) \text{ or } (qx_{i-1},qx_i)=(\xi_{n-1},\xi_{k-1}) .$$

When the LSPs are first calculated and then quantized, x_i and x_{i-1} are known, and the "horizontal coupled-correction" (H-CC) criterion is used [2]:

$$\begin{array}{ll} \text{if} \quad H_n + H_k \ge H_{n-1} + H_{k-1} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_{n-1}, \xi_{k-1}) \\ \text{else} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_n, \xi_k) \end{array} \tag{8}$$

where H_{n-1} and H_n are the horizontal distances from ξ_{n-1} and ξ_n to x_{i-1}, and H_{k-1} and H_k are the horizontal distances from ξ_{k-1} and ξ_k to x_i, as shown in Figure 2. In the case of a quantized domain search, the values of x_i and x_{i-1} are not known, thus the criterion of Equation (8) cannot be used.

The fast conversion proposed by Wolovitz [2], does not use "coupled-correction". A "vertical coupled-correction" (V-CC) criterion analogous to the V-SC criterion, could be used:

$$\begin{array}{ll} \text{if} \quad V_n + V_k \ge V_{n-1} + V_{k-1} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_{n-1}, \xi_{k-1}) \\ \text{else} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_n, \xi_k) \end{array} \tag{9}$$

where V_{n-1} and V_n are the vertical distances from $P'_{10}(\xi_{n-1})$ and $P'_{10}(\xi_n)$ to the x-axis, and V_{k-1} and V_k are the vertical distances from $Q'_{10}(\xi_{k-1})$ and $Q'_{10}(\xi_k)$ to the x-axis.

By simulation using the TIMIT database [5], it was found that this criterion differs significantly from the H-CC criterion. Thus, we propose the following "enhanced vertical coupled-correction" (EV-CC) criterion, whose performance is very similar to the H-CC criterion:

If the zero-crossing is from positive to negative:

$$\begin{array}{ll} \left.\begin{array}{l} \text{if} \quad Q'_{10}(\xi_{m2}) \le 0 \\ \text{and } V_{m2} > V_{m1} \end{array}\right\} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_{n-1}, \xi_{k-1}) \\ \qquad\quad \text{else} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_n, \xi_k) \end{array} \tag{10}$$

else, if the zero-crossing is from negative to positive:

$$\begin{array}{ll} \left.\begin{array}{l} \text{if} \quad Q'_{10}(\xi_{m2}) \ge 0 \\ \text{and } V_{m2} > V_{m1} \end{array}\right\} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_{n-1}, \xi_{k-1}) \\ \qquad\quad \text{else} & \Rightarrow (qx_{i-1}, qx_i) = (\xi_n, \xi_k) \end{array} \tag{11}$$

where ξ_{m1} and ξ_{m2} are the centers of the intervals (ξ_{n-1},ξ_n) and (ξ_{k-1},ξ_k), respectively, and V_{m1} and V_{m2} are the vertical distances from $P'_{10}(\xi_{m1})$ and $Q'_{10}(\xi_{m2})$ to the x-axis.

We also found that, in the search for the *6*-th quantized LSP, qx_6, if the previous quantized LSP, qx_5, takes one of these three values: $qx_5=\xi_n=0.2563$, $qx_5=\xi_n=0.0393$, or $qx_5=\xi_n=-0.1175$, a "coupled-correction" would not preserve the interlacing property. In these three particular cases, the "coupled-correction" is skipped.

4. EXPERIMENTAL EVALUATION

Several versions of the "quantized-search Kabal" algorithm (with different correction criteria) as well as Kabal’s algorithm followed by quantization, were evaluated [5] by measuring spectral distortion on the whole TIMIT database. The resulting average spectral distortion and percentage of outliers are given in Table 1.

It is observed that the algorithm which uses both "horizontal single-correction" (H-SC) and "enhanced vertical coupled-correction" (EV-CC) criteria has a performance which is very close to the performance of Kabal’s algorithm followed by quantization. Hereafter, the name "quantized-search Kabal" refers to this version of the algorithm.

	Spectral Distortion		
Criteria	*average (dB)*	*% 2-4 dB*	*% >4 dB*
V-SC	1.55552	13.88856	0.22244
V-SC + V-CC	1.55218	13.78761	0.19226
H-SC	1.53495	12.43227	0.19335
H-SC + V-CC	1.53368	12.36321	0.19008
H-SC + EV-CC	1.53295	12.35014	0.18946
Kabal + quant.	1.53288	12.34532	0.18884

Table 1: Comparison, using spectral distortion, of different versions of the "quantized-search Kabal" algorithm, and Kabal’s algorithm followed by quantization.

5. COMPUTATIONAL COMPLEXITY

It can be shown that the maximum possible number of polynomial evaluations required by "quantized-search Kabal" is 71 [5]. In practice, the maximum number of evaluations found by simulation on the whole TIMIT database was 68. The total number of operations required by Kabal’s and "quantized-search Kabal" algorithms is given in [5].

The control flow of the "quantized-search Kabal" algorithm is greatly simplified by using two flags to keep track of the conditions tested in the correction criteria [5].

To avoid expensive comparisons, the quantization tables are modified to include, with each quantization level, an index (offset) to the first allowed value of the next quantization table. Also, some flags indicating conditions such as "first element of the table", "last element of the table" and "particular case of qx_5" are stored together with the quantization tables, to simplify the control flow of the algorithm [5].

5.1. DSP56001 Implementation

Kabal’s algorithm followed by quantization and "quantized-search Kabal" were implemented on a DSP56001 (fixed-point commercial DSP processor, with fck=20 MHz). The word-length and scaling required at every node of the algorithms was found following the methodology explained in [4]. The computational load for processing a frame of 30 ms is given in Table 2. It is observed that the proposed "quantized-search Kabal" algorithm needs 66% fewer cycles than Kabal's algorithm followed by quantization.

Algorithm	*Cycles*	*Time* [μs]	*MIPS*
Kabal + quantization	12708	635.4	0.2118
"Q.-search Kabal"	4262	213.1	0.0710

Table 2: Computational load, of "quantized-search Kabal" and Kabal’s algorithm followed by quantization, when implemented on a DSP56001.

6. CONCLUSIONS

In this paper, we have proposed a new algorithm for fast direct conversion from LPC to quantized LSP, with application to the CELP FS1016. This algorithm was named "quantized-search Kabal", and it is based on two new criteria for selection of the closest quantized LSP, to be used in a quantized domain search, in which the actual LSPs are not calculated.

Although the proposed algorithm is more efficient than Kabal’s algorithm (followed by quantization), its utilization is tied to the 34-bits scalar quantization of the CELP FS1016. Nevertheless, this algorithm could find application in spectral quantization systems in which this 34-bit scalar quantization is used as preprocessing, for improving efficiency of further scalar or vector quantization [6].

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