LOW DELAY MULTI-LEVEL DECOMPOSITION AND QUANTISATION TECHNIQUES FOR WI CODING

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ABSTRACT

For efficient coding of speech, it is desirable to separate the slowly and rapidly evolving spectral components to take advantage of their different perceptual qualities. In this paper, we present a multi-level wavelet decomposition mechanism, using low-delay FIR filters, applied to Waveform Interpolation coding. The technique overcomes the substantial delay problems of [2] and identifies a preferred technique for the quantisation of the decomposed surfaces. Phase is shown to be particularly sensitive to the compounding of quantisation errors within the tree-structured transform. The proposed solution involves the use of VDVQ on separately decomposed magnitude/phase surfaces. This approach provides for coarse or no phase quantisation while maintaining high speech quality. The techniques discussed may also be applied to other transforms and to the quantisation of surfaces in the standard Waveform Interpolation coder.

1. INTRODUCTION

The need to efficiently quantise signals to maximise the transmission channel utilisation, while still maintaining high quality, has led to the exploitation of human speech perception. In particular, for high perceptual quality, it is necessary to preserve the correct degree of periodicity of the speech. This result is employed in coders based on pitch-cycle waveforms (known as characteristic waveforms (CW)) such as the Waveform Interpolation (WI) coder [1]. To quantise the speech more efficiently, it is advantageous to isolate the underlying pulse shape from the signal evolution. This requires some mechanism to decompose the evolutionary signal into frequency subbands. The original decomposition method of WI involves simple filtering of the CW surface in the evolution domain. The outcome is a slowly evolving waveform (SEW) representing the periodic component of speech, and a rapidly evolving waveform (REW) containing the random noise-like component. To further decompose the signal, we proposed a multirate digital filter bank approach using finite impulse response (FIR) wavelet filters [2]. In contrast with [6], for this work the wavelet decomposition was performed on oversampled pitch-cycle waveforms, so as to maintain a fixed transmission rate. This technique integrated well into the WI framework, however, it had the disadvantage of incurring long system delays, making the decomposition impractical for real-time applications. The issue of delay was addressed in [3] with the proposal of infinite impulse response (IIR) quadrature mirror filter banks. Substantial delay reductions result from IIR techniques, however, the decomposition proves to have high sensitivity to low-rate quantisation of the surfaces.

In this paper, we present a multi-level decomposition technique using low-delay FIR filters. We retain the non-recursive nature of FIR filters while having the ability to impose a very low delay. Advantages of the proposed decomposition include scalability in quantisation, multi-scale signal evolution analysis, and low delay which makes the decomposition compatible with real-time speech coding. Quantisation of the decomposed surfaces is a non-trivial issue, and therefore, several quantisation and reconstruction techniques are analysed.

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2. LOW DELAY FIR FILTERS

The multi-resolution wavelet decomposition based on Quadrature Mirror Filter (QMF) banks has an inherently long system delay and thus has limited application in the field of real-time speech processing. A possibility for reducing the delay is to use filters with lower delay for the inner layers, since in a tree-structured system, the decomposition levels located further inside the tree contribute more significantly to the overall delay than the outer stages.

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and group delays for $H_0(z)$ and $G_0(z)$, the analysis and synthesis lowpass filters respectively, are given in Figure 1. Note, $G_0(z)$ and $H_1(z)$, the analysis highpass filter, are related by the equation $G_0(z) = H_1(-z)$.

3. DECOMPOSITION OF THE CW SURFACE

The CWs are sampled at a constant rate of 320Hz and are thus oversampled, though not by a constant degree (due to the natural pitch track variation of the speech). Further, since the CWs are not extracted pitch synchronously, or with attention to phase, it is necessary to align the CWs. In this work all CWs were aligned to a common pulse waveform before decomposition so as to remove overall phase offsets. In the time domain such offsets correspond to rotation of the pitch-length waveform. Several methods of decomposition of the aligned CW surface were tested:

1. Filtering of Time Domain Characteristic Waveforms
2. Frequency Domain Techniques:
   a) Real/Imaginary
      The Real and Imaginary components of each CW coefficient are separately decomposed by the filter bank. If required magnitude and phase are calculated on the final surfaces.
   b) Separate Magnitude/Phase
      The magnitude and phase of the DFT coefficients of the CWs were separated and filtered individually. To avoid phase wrapping, unity magnitude complex values were used to represent phase.

Note that the surfaces obtained by the two frequency domain techniques have different characteristics. While the highpass surfaces for the Real/Imaginary decomposition exhibit rapid changes in magnitude and phase, the magnitude decomposition of the Separate Magnitude/Phase technique neglects any phase variations. Thus, a section of speech with slow magnitude evolution but rapid phase evolution will dominate a highpass surface in the Real/Imaginary decomposition, but will be passed by a lowpass filter in the Magnitude/Phase case. Comparison of the decomposed surfaces for the two frequency domain techniques showed that the phase surfaces possessed similar characteristics. The magnitude surfaces were smoother in the case where the magnitude and phase were separated before filtering. When converted to the time-domain, the pulse shape was still visible in the highpass surfaces for the Real/Imaginary decomposition, whereas the surfaces were uncorrelated in the Magnitude/Phase case.

4. PARAMETER SENSITIVITY

Evangelista [6] suggests scalar quantisation schemes for his pitch-synchronous wavelet transform (PSWT) surfaces. Indeed, our results show that very coarse quantisation (2-4 bits) of individual magnitude and phase components maintains high quality output speech. This result suggests that while the exact magnitude and phase values are not significant, the trend of these values is important. This is particularly true with the phase parameter.

To test the sensitivity of phase to quantisation errors, random noise was added to the phase of the surfaces (the original magnitude of the parameters was maintained). The permissible level of Gaussian additive phase noise prior to audible distortion was measured. Of the three innermost phase surfaces (refer Figure 2), highpass 2 was the least sensitive, with added noise of variance 1.0 radians maintaining good performance. Noise with variance 0.6 radians was the maximum allowed before distortion for highpass 3, while noise of variance greater than 0.2 radians added to the phase of the lowpass 3 surface created distortion. Thus the phase of the highpass surfaces can be judged to be significantly less sensitive than that of the lowpass, scale surface. This concurs with the phase assumptions made in the standard WI coder. However, as explained in Section 5.2 the dependence of the Wavelet decomposition on phase and phase surface interrelationships adds a significant dimension to the phase quantisation/representation problem. Such dependencies are particularly relevant when considering the use of VQ schemes for surface quantisation.

5. QUANTISATION

An advantage of the multi-level wavelet decomposition is that the transmission frequency required for the surfaces is defined, due to the decimation. Each surface is sent at a rate
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and group delays for \(H_0(z)\) and \(G_0(z)\), the analysis and synthesis lowpass filters respectively, are given in Figure 1. Note, \(G_0(z)\) and \(H_0(z)\), the analysis highpass filter, are related by the equation \(G_0(z) = H_0(-z)\).

### 3. DECOMPOSITION OF THE CW SURFACE

The CWs are sampled at a constant rate of 320Hz and are thus oversampled, though not by a constant degree (due to the natural pitch track variation of the speech). Further, since the CWs are not extracted pitch synchronously, or with attention to phase, it is necessary to align the CWs. In this work all CWs were aligned to a common pulse waveform before decomposition so as to remove overall phase offsets. In the time domain such offsets correspond to rotation of the pitch-length waveform. Several methods of decomposition of the aligned CW surface were tested:

1. Filtering of Time Domain Characteristic Waveforms
2. Frequency Domain Techniques:
   a) Real/Imaginary
      The Real and Imaginary components of each CW coefficient are separately decomposed by the filter bank. If required magnitude and phase are calculated on the final surfaces.
   b) Separate Magnitude/Phase
      The magnitude and phase of the DFT coefficients of the CWs were separated and filtered individually. To avoid phase wrapping, unity magnitude complex values were used to represent phase.

Note that the surfaces obtained by the two frequency domain techniques have different characteristics. While the highpass surfaces for the Real/Imaginary decomposition exhibit rapid changes in magnitude and phase, the magnitude decomposition of the Separate Magnitude/Phase technique neglects any phase variations. Thus, a section of speech with slow magnitude evolution but rapid phase evolution will dominate a highpass surface in the Real/Imaginary decomposition, but will be passed by a lowpass filter in the Magnitude/Phase case. Comparison of the decomposed surfaces for the two frequency domain techniques showed that the phase surfaces possessed similar characteristics. The magnitude surfaces were smoother in the case where the magnitude and phase were separated before filtering. When converted to the time-domain, the pulse shape was still visible in the highpass surfaces for the Real/Imaginary decomposition, whereas the surfaces were uncorrelated in the Magnitude/Phase case.

### 4. PARAMETER SENSITIVITY

Evangelista [6] suggests scalar quantisation schemes for his pitch-synchronous wavelet transform (PSWT) surfaces. Indeed, our results show that very coarse quantisation (2-4 bits) of individual magnitude and phase components maintains high quality output speech. This result suggests that while the exact magnitude and phase values are not significant, the trend of these values is important. This is particularly true with the phase parameter.

To test the sensitivity of phase to quantisation errors, random noise was added to the phase of the surfaces (the original magnitude of the parameters was maintained). The permissible level of Gaussian additive phase noise prior to audible distortion was measured. Of the three innermost phase surfaces (refer Figure 2), highpass 2 was the least sensitive, with added noise of variance 1.0 radians maintaining good performance. Noise with variance 0.6 radians was the maximum allowed before distortion for highpass 3, while noise of variance greater than 0.2 radians added to the phase of the lowpass 3 surface created distortion. Thus the phase of the highpass surfaces can be judged to be significantly less sensitive than that of the lowpass, scale surface. This concurs with the phase assumptions made in the standard WI coder. However, as explained in Section 5.2 the dependence of the Wavelet decomposition on phase and phase surface interrelationships adds a significant dimension to the phase quantisation/representation problem. Such dependencies are particularly relevant when considering the use of VQ schemes for surface quantisation.

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Figure 1. Two-band filter bank with 8-tap filters. System delay is one sample (a) Magnitude Response (b) Phase Response (c) Group Delay

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In [6], the PSWT is encoded using Adaptive PCM (APCM) for the highpass surfaces, and an 8-bit uniform quantiser for the lowpass 3 surface. The results given were based on the performance of the PSWT on a single vowel sound. While the paper fails to comment on the performance during an utterance containing voiced and unvoiced speech, the high proposed bit rate of 21 kbits/sec for the transform coefficients alone, or even the reduced rate of 9 kbits/sec, when the two higher rate surfaces were omitted, are impractical for low-rate speech compression. In contrast, here we propose several vector quantisation techniques. These potentially lower the overall coder bit rate to 2.4 kbits/sec. In addition, we add significantly to the work of [6] by discussing the necessary relationships between the decomposed surfaces to provide perceptually accurate reconstruction.

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made to the VDVQ training algorithm to cope with phase
wrapping. For the Frequency domain Real/Imaginary
decomposition, magnitude and phase were calculated for each
coefficient. The absolute phase was then converted to a unity
magnitude phase vector for training. This unity magnitude was
rectified after each codebook update.

One method of maintaining the phase relationships is to place
limits on the phase vector selection for the highpass surfaces
once the phase has been chosen for the lowpass surface, rather
than quantising all phases independently. As an alternative
approach, the phase of the CW surface may be quantised. This,
however, results in multiple transmissions of the phase, which
takes advantage of neither the lower-rate surfaces of the wavelet
decomposition nor human perception of phase.

5.3 Time-Domain Quantisation

VDQ can also be used to encode the surfaces formed by
decomposing the time-domain CWs. However, a difficulty arises
since phase information is still contained in the surfaces, and is
not able to be controlled explicitly. This results in noisy output
speech even with large codebooks.

6. RECONSTRUCTION

The reconstruction techniques for the three decomposition
methods are:

1. Reconstructing Time Domain Characteristic Waveforms
Reconstruction of the CW surfaces follows a direct reversal of the
decomposition, in which the innermost lowpass and highpass
surfaces are upsamples, filtered by the synthesis mirror filters,
then combined to form the lowpass surface of the next highest
level.
Figure 3. Structure of three-level wavelet reconstruction using the Frequency Domain: Separate Magnitude/Phase method, where $v_{q}(k)$ is the evolutionary signal, $G_{q}(x)$ is lowpass and $G_{q}(x)$ is highpass.

2. Frequency Domain Techniques:
   a) Real/Imaginary
   Some phase models were experimented with to represent the phase of the individual surfaces, but with poor results. To improve the quality, transmission of quantised phase is required.
   b) Separate Magnitude/Phase
   Magnitudes and phases are reconstructed separately, with each surface reconstructed and upsampled to the original sampling frequency as shown in Figure 3. By reconstructing all surfaces individually, the phase of one surface may be adjusted, without affecting the phase of other surfaces. This allows, for example, the application of random phase to the third level highpass surface without affecting the phase of higher surfaces. This makes the use of phase models effective, and the need to quantise phase, unnecessary.

In existing coders, such as the waveform interpolation and sinusoidal coders, phase models are used [8]; some requiring a voiced/unvoiced decision. The approach taken in the Separate Magnitude/Phase reconstruction was to apply random phase to the recomposed highpass surfaces, while a linear phase model was used for the lowpass surface. This phase linearity was randomised during periods of unvoiced speech. The measure of the level of disruption of the phase linearity was found by comparing the energy contained in the lowpass surface to that of the corresponding highpass surface. This corresponds to a dynamic voiced/unvoiced mix measurement. In addition, the amount of added noise can be weighted by the inverse of the LPC power spectrum, to ensure that formant frequencies are not distorted.

7. RESULTS

For best results, the magnitude and phase of the characteristic waveform surface were decomposed separately. Using this method, magnitude codebooks could be small and phase did not require quantisation. By choosing a good phase model and adapting this to control the amount of CW correlation required, good quality output speech could be achieved with minimal buzziness or reverberation.

While phase is perceptually important in speech, the intersurface phase relationships of the decomposition require accurate transmission for good reconstruction. Due to the conjugate mirror symmetry of the filter banks, quantisation errors result in non-cancellation of aliased components. These errors compound through the tree-structure of the transform, causing any errors due to the encoding of the inner surfaces to be magnified greatly.

8. CONCLUSION

The wavelet decomposition method using low-delay FIR filters allows a multi-resolution analysis of the signal evolution. The complications associated with the quantisation of the decomposed surfaces have been identified. In particular, phase is important in the wavelet decomposition. The key to good quantised speech lies in the ability to separate the magnitude and phase in the decomposition and reconstruction. This removes the need to quantise the phase of the surfaces and hence the compounding phase quantisation errors which lead to perceptually annoying CW phase behaviour. Further through exploiting separation of magnitude and phase it is possible to take advantage of well-established perceptual qualities of voiced and unvoiced sounds.

The wavelet decomposition and quantisation techniques discussed in this paper may also be applied to other transforms, such as those operating pitch-synchronously in [9].

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