

EXTENDING EFFICIENT SPECTRAL ENVELOPE MODELING TO MEL-FREQUENCY BASED REPRESENTATION

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ABSTRACT

In this work we consider the problem of spectral envelope estimation using spectra with perceptually warped frequency axis. The goal of this work is the reduction of the order of the spectral envelope model which will facilitate the use of these envelopes for training of voice conversion systems. We adapt the True-Envelope estimator to Mel-frequency representations and adapt a recently proposed cepstral model order selection criterion taking into account the distortion of the frequency axis. We evaluate the modified order selection procedure using a perceptual framework for the evaluation of envelope estimation errors. The experimental evaluation carried out with real speech confirms our modifications. The results demonstrate that the mel frequency based true envelope estimator achieves superior envelope estimation with significantly reduced model order.

Index Terms— speech synthesis, speech analysis, envelope detection, speech codecs, speech enhancement.

1. INTRODUCTION

The estimation of the spectral envelope represents one of the main tasks performed in several speech and audio processing applications. Defined as the smooth function passing through the prominent peaks of the spectrum, the spectral envelope is generally considered as one of the determining factors for the timbre of a sound. Accordingly, the quality of systems performing voice or timbre modification depends significantly on the quality of the envelope estimate.

The selection of the proper filter model (AR, MA, ARMA) and the corresponding model order are considered the main issues if aiming to perform efficient estimation, since they both are generally unknown. Autoregressive and cepstrum based methods are commonly used as envelope models. The main problems observed in such methods are the fact that they do not modelize the expected envelope, and that the model order is rarely adapted to the characteristics of the signal. On the other hand, efficient spectral envelope estimation can be achieved by means of the True-Envelope estimator (TE) [1]. Following [2], an optimal order selection is derived in terms of the F_0 and the sampling rate. However, for high-quality signals such selection could lead to high order values.

Human perception is frequently considered to reduce the dimensionality of parametric representations of the spectral information. It is well known that not all the information of the observed spectrum is equally important since a logarithmic scaling of the frequency axis is closer to the resolution used by the ear to perceive

sound. We found that some envelope models considering such frequency scaling as the well-known Mel-Frequency Cepstral Coefficients (MFCC) and Warped Linear Prediction (WLPC) [3] are not well adapted to achieve signal modification since MFCC represents mainly the frequency-bands energy shape, while the envelopes deduced by WLPC include the harmonic structure. However, we argue that the application of frequency scaling in the TE method should lead us to achieve efficient modelisation of perceptually frequency-scaled spectra.

In this article we extend the estimation performed by TE and its autoregressive version (TELPC) to Mel-frequency based representations in order to reduce the model complexity when applying the order selection described in [2]. In this way we aim to obtain a reduced parametric model minimizing the perceptual effect of the missed envelope details. Also, we propose an adaptation of the order selection procedure by taking into account the frequency-axis warping. Finally, instead of typical spectral distortion measures, we propose the use of perceptive criteria inspired by the PESQ standard [4] to quantify the modeling error and evaluate the order selection adaptation.

The work is organized as follows. The efficient True-Envelope estimator and the order selection are described in section two. Mel-frequency scaling applied to True-Envelope and its autoregressive version are presented in section three and four. The methodology used for a perceptual evaluation of spectral envelope estimations is addressed in section five. An experimental evaluation of the proposed methods including the well-known technique based on linear prediction is found in section six. We finish the work in section seven with some conclusions.

2. IMPROVED CEPSTRUM-BASED SPECTRAL ENVELOPE MODELING

There are various techniques for cepstrum-based envelope estimation. In [1] an efficient spectral envelope estimator called True-Envelope (TE) has been presented. This iterative technique allows efficient estimation of the spectral envelope [5] without the shortcomings of the discrete cepstrum [6]. The resulting estimation can be interpreted as a band limited interpolation of the major spectral peaks.

2.1. Order selection

A major advantage of the cepstral envelope estimation techniques is that a reasonable estimate of the optimal cepstral order can be provided. If the observed signal has the fundamental frequency F_0 ,

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the harmonic excitation spectrum samples the resonator filter with a sampling rate given by F_0 . Therefore, one may deduce that the information from the original filter that exceeds the related Nyquist bandlimit in the cepstral domain is lost. Accordingly, a theoretical proper bound for the cepstral order can be obtained [2] in the form

$$\hat{O} = \frac{FS}{2F_0} = \alpha \frac{FS}{F_0}, \quad \alpha_c = 0.5 \quad (1)$$

While the real optimal order, that is the order that provides an envelope estimate with minimum error, depends on the specific properties of the envelope spectrum, the order selection according to (1) is reasonable for a wide range of situations and the resulting error has been found through experimentation to be rather close to the one obtained with the real optimal order.

3. EFFICIENT FREQUENCY-WARPED ENVELOPE ESTIMATION

3.1. Mel-scaled True-envelope estimation

Mel scale is considered as an accurate representation of the frequency precision of human perception. The use of these scales has been found to be advantageous since it allows a compression of the spectral information minimizing the perceptual effect of missed information. Accordingly, in our proposition the spectrum used by the True-Envelope estimator algorithm will be warped using a Mel-based function in order to obtain a perceptual resolution on the estimated envelope. We will refer to the resulting method as the Mel True-Envelope estimator.

3.2. Adaptation of the order selection to a warped representation

Following the ideas of order selection for cepstral models outlined above, an efficient order selection would depend on frequency due to the frequency-dependant warping factor. If the spectral envelope is represented in terms of a single cepstral model, however, the order has to be fixed. Moreover, the question arises which frequency band should be selected to guide the order selection process such that perceptually the envelope obtained in the mel frequency representation is as close as possible to the real envelope. Based on perceptual cues, we argue that the fact that we are mainly interested in a precise estimation at low frequencies give us a reason to propose an adaptation of the order selection based on the lowest Δ_{F_0} . This value is found at the position of the first F_0 partial after frequency warping since we apply the Mel-scaling in a way that the axis limits are preserved (for $F_{(Hz)} = 0, FS/2, F_{(melHz)} = 0, FS/2$). Accordingly, the adaptation can be simplified to apply the inverse of the corresponding mel scaling factor at $F = F_0$ to the α parameter in (1). Therefore, the resulting α value should be found around 0.15 while $F_0 < 1e3Hz$ since the bark scaling is linear for $F < 1e3Hz$. Clearly, this adaptation leads to reduced order values.

Note that the degree of optimality of the selection is limited, as mentioned above, by the increasing mismatching of Δ_F as the frequency value increases on the mel-scaled axis, which could result, in general, in a slight shift of α towards higher values. We remark that this correction effect depends greatly on the voicing nature of the observed spectrum since it considers only the region where the envelope is defined by the harmonic peaks.

4. IMPROVING ALL-POLE FREQUENCY-WARPED ENVELOPE MODELING

Spectral estimation based on frequency-warping is commonly done by replacing the unit delay elements of a conventional linear filter structure by first-order allpass filters. In [3], this technique, also known as Warped Linear Predictive Coding (WLPC), is described in detail and compared with the conventional LPC technique. As for the proposed MTELPC method, the aim of this technique is to perform an AR based estimation of a frequency warped version of a spectrum. The problem we found in WLPC stems from the fact that the featured envelopes do not match the definition of spectral envelope since the most of the harmonic peaks at low frequencies are included in the estimation.

This characteristic could appear advantageous for inharmonic excitation signals or applications looking to keep the F_0 information (i.e. speech coding). However, for signal modification proposals our interest is to separate the contributions given by the source and filter components in order to achieve independent timbre and pitch modifications.

Note, that the spectral flatness measure used as a performance measure in [3] is not well adapted to harmonic spectra since, as opposed to the one defined in [7], it takes into account the whole spectrum. In consequence, the improvement shown by WLPC by means of this measure is mostly interesting for unvoiced speech.

On the other hand, once a proper order is selected to perform a MTE estimate, it can be used as shown in [7] to fit an all-pole model of the frequency warped representation. We denote this method as the Mel-based True-Envelope LPC (MTELPC). As stated in the first section, the estimation performed by True-Envelope follows the shape defined by the spectral peaks and not the peaks itself for either linear or warped frequency resolutions. Therefore, MTELPC is expected to match, at difference of WLPC, the desired shape without extracting the harmonic structure of the spectrum.

Note that MTELPC performance will be limited firstly by the MTE estimate given as input of the autoregressive model and secondly by the order of the autoregressive model itself. To resolve the first point, we are especially interested in using an adequate order selection criteria, as the one we proposed in the previous section. Once the MTE is defined, we can deduce that the resulting all-pole envelope will become closer to the MTE estimate as the model of the AR system grows.

5. PERCEPTUAL EVALUATION OF SPECTRAL ENVELOPE ESTIMATION

A problem of the evaluation of spectral envelope models by means of simply comparing the differences of the transfer functions is that the perceived impact of the differences is not taken into account. Therefore, we propose to compare the envelope estimations related to a reference using a perceptual framework where the operations performed at the ear affecting the featured envelope are included. In this way, considering the current state of the art of speech and audio quality evaluation, we followed some concepts found in the PESQ standard[4] to include perceptual criteria in our evaluation. Firstly, the use of a perceptually-based frequency resolution. Secondly, the consideration of the middle-ear filter which applies a frequency dependent attenuation of the spectral energy and the use of a spectral representation based on the concept of loudness. Finally, the consideration of perceptual bands, as performed by the inner ear.

Note that when the evaluation is carried out using real speech signals, the comparison between the estimates and the real informa-

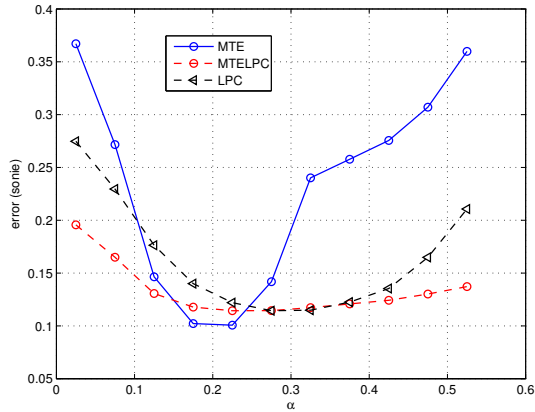


Fig. 1. Perceptual error as a function of the local α (male speaker). In all cases MTELPC uses $\alpha = 0.15$ for the MTE estimate.

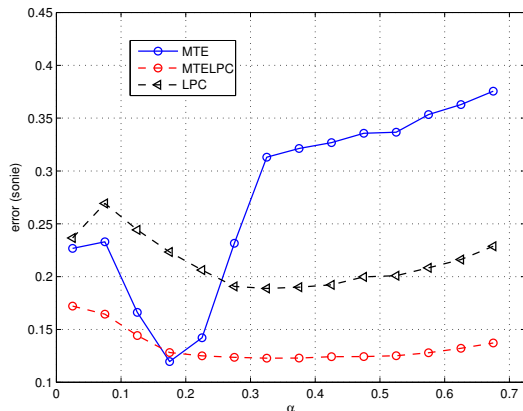


Fig. 2. Perceptual error as a function of the local α (female speaker). In all cases MTELPC uses $\alpha = 0.15$ for the MTE estimate.

tion is not straightforward. This is because we have no access to the underlying transfer function but to the subsampled version defined by the current F_0 . In [2] it has been shown that the interpolation performed by the linear TE using order selection is considered to be the best approximation of the corresponding resonator filter. In addition, we are specifically interested in the perceptual degradation due to the reduced high-frequency information of the warped envelope. Accordingly, for experimentation proposals we can use the estimates of linear TE as the reference envelopes. The resulting modeling error when comparing both reference and evaluation envelopes (obtained from the MTE, MTELPC and LPC methods) is also averaged at each perceptual band.

6. EVALUATION ON REAL SPEECH

6.1. Procedure

Firstly, we were interested in evaluating the α parameter for the MTE order selection. Once a proper value was defined, it was used to

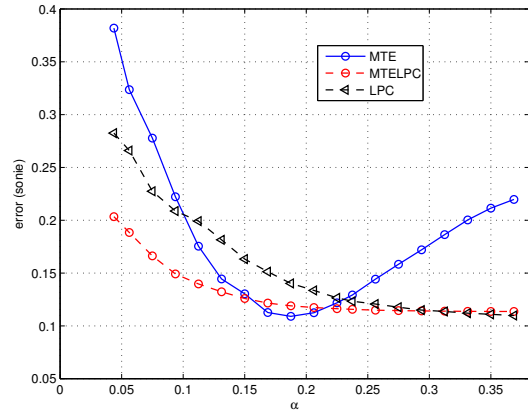


Fig. 3. Perceptual error as a function of the average α (male speaker). In all cases MTELPC uses $\alpha = 0.15$ for the MTE estimate.

perform MTELPC estimates in order to carry out a comparison of the estimation performance among LPC, MTE, and MTELPC using the perceptive model previously outlined. We used real speech signals from a male and a female speaker so that we could also evaluate the order selection related to the mean F_0 of the speaker. For the three methods, we used several model orders within the range $\hat{O} = [7, 59]$. This range, and the one defined by the F_0 values, covers approximately α within the range $[0, 0.7]$. On the other hand, a discrete grid was defined to quantify the resulting α value in function of the F_0 value and the analysis order at each frame. TE estimation with order selection is also performed since it will represent our reference envelope. Ten-thousand frames (75 percent of them considered as voiced) were analyzed for each speaker, corresponding to approximately 40 short phrases. The mean F_0 values for the male and female speaker are close to 150Hz and 240Hz , respectively.

6.2. Results

As for the TE method, the resulting error of MTE showed a parabolic form and its minimum was found to be, as expected, slightly higher than the proposed value ($\alpha=0.15$), as shown in the line corresponding to TE in fig. 1 for the male speaker. This is especially clear in fig. 2, which corresponds to the female speaker case and then the mean F_0 is significantly higher.

We computed the MTELPC estimates fixing the resulting α value to 0.15 since we are specifically interested in evaluation the effect of the AR model order when using already optimized MTE estimation. The results are already included in fig. 1 and fig. 2. As we stated before, it showed an improved performance for increasing α , which can be explained by the increasing capacity of the AR model to fit the underlying MTE estimate. We remark, however, that the best result of MTELPC can not outperform the one of MTE.

LPC was found to perform worse than the MTE based methods, as is also shown in the figures. As expected, this effect increases for increased F_0 since it makes also increase the aliasing of the autocorrelation function used by LPC [8].

In order to measure the effect of the voicing nature we carried out the evaluation without any voicing discrimination criterion on the frames. In theory, this is beneficial to LPC since it represents the

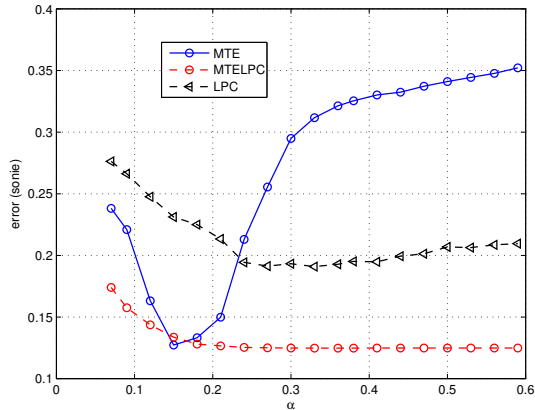


Fig. 4. Perceptual error as a function of the average α (female speaker). In all cases MTELPC uses $\alpha = 0.15$ for the MTE estimate.

best method for envelope estimation of inharmonic spectra. Also, it clearly reduces the cases where the order selection has a theoretical basis. Despite this fact, the improvements shown by LPC were not significant, affirming the proposed α value as a proper choice.

We also considered the case when the model order remains unchanged since many applications are generally restricted to this condition. Principally, we aim to measure the optimality of the order selection in MTE when considering only the mean F_0 . For MTELPC only the AR model order remains unchanged since, as the previous test, the selection criterion denoted by $\alpha = 0.15$ is already considered at each analysis frame to compute the input MTE estimates. The results are shown in fig. 3 and fig. 4 and are found to be rather similar to those obtained using variable order. We can therefore state that average order selection should be preferred over any arbitrary criterion when the model order must remain unchanged.

Taking into account the modeling error per perceptual band, let us also clarify the effect of the local adaptation of α to the frequency addressed before. We show in fig. 5 the resulting error-surface of the MTE modeling error related to α within each perceptual band. Clearly, the α value corresponding to the minimal error at each perceptual band (solid line) follows the local scaling of δ_F (dotted line) after warping of the frequency axis. This view also lets us appreciate the fact that, compared to LPC, by using MTE based methods with order selection we are primarily maximizing the matching of the estimated envelope on the low-band region, which is, clearly, perceptually preferable.

7. CONCLUSIONS

In this work, we have presented an adaptation of the cepstrum based True envelope estimator for Mel-scale frequency axis warping. The previously known order selection criterion has been adapted taking into account the effective frequency warping. An evaluation framework based on perceptual criteria was proposed to estimate the perceptual impact when measuring envelope differences. The experimental comparison to linear predictive envelope estimation demonstrates that the Mel-frequency representation of the spectra allows us to achieve equivalent (for low pitch signals) or significantly improved (for high pitch signals) spectral envelope estimations with

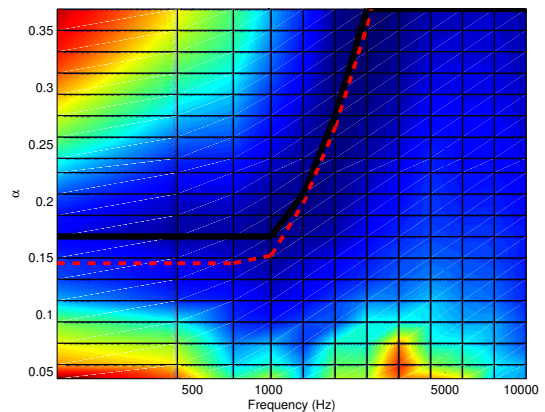


Fig. 5. Perceptual error (intensity) as a function of α and the frequency band (male speaker), MTE estimation. At each band, the solid line follows the resulting minimal error location while the dotted one represents the theoretical α value considering the local frequency warping.

significantly reduced model orders. Further subjective tests will be carried out in the future to demonstrate the reliability of the perceptual evaluation framework.

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