Quality Analysis of Macroprosodic $F_0$ Dynamics in Text-to-Speech Signals

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Abstract

We present a study on the relation between fundamental frequency ($F_0$) and its perceptual effect in the context of text-to-speech (TTS) synthesis. Features that essentially capture the intonational (macro-prosodic) properties of spoken speech are introduced and analysed with respect to the following questions: (i) How does the prosodic variation of TTS signals differ from natural speech? (ii) Is there a functional relationship between the prosodic variation of TTS signals and its perceived quality? In answering these questions we present novel approaches for the construction of non-intrusive quality estimators. The results reveal a substantial degree of systematic influence of prosodic variation on TTS quality.

\textbf{Index Terms}: Speech quality, instrumental quality assessment, text-to-speech (TTS), prosody.

1. Introduction

The wish to evaluate speech quality with the aid of instrumental measures, that is to provide an estimate of subjective speech quality by algorithmic means, concerns most researchers who modify a speech signal, for example by noise reduction or coded transmission. A special case of this objective applies to text-to-speech (TTS) research, where a \textit{generated} speech signal needs to be evaluated with respect to its perceptual quality. In the literature, efforts to develop a reliable instrumental estimator of TTS \textit{signal quality} are mostly directed towards the detection \cite{1} and perceptual quantification \cite{2} of concatenation artefacts, since systematic deficits of prosodic $F_0$ variation that can be extracted from the acoustical signal alone. Second, insights into the construction of a non-intrusive quality measure are given that tie up to a recent study headed towards instrumental measurement of prosodic TTS quality \cite{9}.

The paper is organised as follows: In Section 2, a set of prosodic parameters, also denoted as features, is introduced. The use of speech material is described in Section 3. In Section 4, we compare parameter statistics for synthetic and natural speech signals. In Section 5, an approach to perceptual modelling is presented. The results are discussed in Section 6. The paper closes with conclusions.

2. Prosodic Parameters

The set of prosodic features is denoted as $X = \{x_1, \ldots, x_n\}$. Individual features $x_i = \{x_{i1}, \ldots, x_{im}, \ldots, x_{iN}\}$ all manifest as one time-aggregated scalar $x_{im}$ per signal (stimulus). $N$ is the number of observations (stimuli) of the dataset under test (see Section 3). The choice of features ($I = 14$) was guided so as to allow for general insight into $F_0$ variation in TTS on one hand, and to focus on those features which have shown best performance for perceptual quality modelling on the other hand, see \cite{9}. Let $F_0(l,v)$ be the pitch contour of the $l$-th voiced segment, characterised by $F_0(l,v) \neq 0$, with $l = 1, 2, \ldots, L$ and $v = 1, 2, \ldots, V$. $L$ denotes the number of voiced segments per signal and $V$ is the number of $F_0$ samples extracted at a rate of 100 Hz using \textit{Praat} \cite{10}. Median filtering is applied to alleviate outliers. The following well-known parameters are considered first: $\Delta F_0$ (range), $\sigma F_0$ (standard deviation), and $\overline{F_0}$ (mean). These parameters are applied signal-wise to the voiced-only $F_0$ curve (i.e., $L = 1$) which is gauged to the logarithmic semitone (st) scale \cite{4}, referenced to the minimum $F_0$ value:

$$F_0(l,v) \text{[st]} = 12 \cdot \log_2 \frac{F_0(l,v) \text{[Hz]}}{\min_{l,v} (F_0(l,v) \text{[Hz]})}. \quad (1)$$

This normalisation can be interpreted as an $F_0$-specific speaker normalisation, with the additional effect that the range is equivalent to the maximum $F_0$.  

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From the literature [4], it is known that the perception of $F_0$ (e.g., pitch distance and pitch change) is substantially influenced by perceptual auditory thresholds. Moreover, intonational properties of $F_0$ parameters, calculated from the slope $m_{seg}$ of the least-squares regression line fitted through the segments $F_0(l, v)$. The *peakedness ratio* (PR) is defined as the relative number of segments per signal whose magnitude of $m_{seg}$ is above a threshold $\xi$,

$$
PR = \frac{1}{L} \sum_{l=1}^{L} \delta_{\xi} \left( \left| m_{seg} \{ F_0(l, v) \}_{v=1,...,V_l} \right| \right),
$$

with the step function $\delta_{\xi}(x)$ defined as:

$$
\delta_{\xi}(x) = \begin{cases} 
1, & \text{for } x > \xi \in \mathbb{R}^+ \\
0, & \text{else.}
\end{cases}
$$

The *drop ratio* (DR) expresses the fraction of declining segments:

$$
DR = \frac{1}{L} \sum_{l=1}^{L} \delta_{\xi} \left( -m_{seg} \{ F_0(l, v) \}_{v=1,...,V_l} \right).
$$

Finally, we take into account the *variability ratio* (VR), which gives the relative number of segments with a mean derivative above $\xi$:

$$
VR = \frac{1}{L} \sum_{l=1}^{L} \delta_{\xi} \left( \frac{1}{V_l} \sum_{v=1}^{V_l-1} |F_0(l, v) - F_0(l, v + 1)| \right).
$$

The thresholds are set in accordance with [9], gender-discriminative to the values given in Table 1. (1) is not used for features PR, DR, and VR as their ability to describe the perceptual effect has not been found to significantly improve through logarithmic compression. In the scope of this study, we further include the per-signal means and standard deviations of the arguments of the step function in (2), (4), and (5), which are beyond the corresponding thresholds. These arguments are the regression slopes $|m_{seg}|$, $m_{seg,D}$ and the mean derivative $|F_0^D|_{i,v}$ per voiced segment, respectively. In [9] eleven rhythm (timing) parameters have been investigated concerning their capabilities to describe TTS quality. To reduce overload, we consider 2 parameters here that have proven robust and are purely derived from $F_0$: The percentage of total voiced duration per signal (%V) and the average duration of voiced segments $T_{voi}$ in milliseconds.

### 3. Speech Databases

Details of two speech signal databases are given in the following. First, a broad TTS database for which extensive auditory tests have been conducted is described. Second, a natural speech corpus is presented that is used for reference purposes.

#### Table 1: Settings of threshold $\xi$.

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>MALE</th>
<th>FEMALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR, DR</td>
<td>0.325 [ms/10 ms]</td>
<td>0.55 [ms/10 ms]</td>
</tr>
<tr>
<td>VR</td>
<td>0.65 [ms/10 ms]</td>
<td>1.1 [ms/10 ms]</td>
</tr>
</tbody>
</table>

#### 3.1. TTS Database

The perceptual quality of TTS signals has been analysed within the framework of a semantic differential, carried out at T-Labs Berlin, Germany [5]. Ten German sentences were prepared such that none of them contained words out of the scope of German dictionaries (e.g., proper names). The average spoken stimulus length was about 10 s. For synthesis, 14 and 15 different state-of-the-art TTS systems (concatenation and HMM-based) with female and male voices, respectively, were used. All speech files were downsampled to 16 kHz and level-normalised to -26 dBov. Thirty naïve listeners rated $N = 30$ stimuli per gender on 16 attribute scales. These scales have been determined in two separate pretests [5]. Each TTS system was represented by at least 2 randomly chosen stimuli. Factor analysis revealed a three-dimensional quality model. The dimensions (factors) are named (1) naturalness, (2) disturbances, and (3) temporal distortions. In the scope of this study we consider the per-stimulus factor scores from a Principal Component Analysis (Varimax rotation) as target variable $y_f = \{y_{1f},...,y_{Nf}\}$. $f = 1, 2, 3$. The factor ordering (1-3) thus corresponds to their perceptual importance in terms of explained variance of the auditory ratings.

#### 3.2. Natural Speech Database

In order to allow for a comparison between synthetic and natural speech, the 10 sentences that have been synthesised (see Section 3.1), have also been recorded from 4 male and 4 female human (amateur) speakers. This yields 40 signals per gender. All files are processed to have a sampling frequency of 16 kHz and a normalized speech level of -26 dBov.

#### 4. Comparison of TTS vs. Natural Speech

The feature set from Section 2 is analysed in a comparison between synthetic and natural speech using classical statistical figures. In Table 2, arithmetic means and standard deviations of features $x_i$ are denoted as $\mu$ and $\sigma$, respectively, and given separately for both genders. The complete speech material described in Section 3 has been used. The statistical figures reveal a fairly clear message: $F_0$ dynamics in TTS are well below those of natural speech. Nearly all parameters show a remarkable difference in the mean, qualitatively consistent for both genders.

#### Table 2: Arithmetic means $\mu$ and standard deviations $\sigma$ of features $x_i$, given per gender for TTS signals and natural speech signals.

<table>
<thead>
<tr>
<th>$x_i$</th>
<th>TTS</th>
<th>NATURAL</th>
<th>TTS</th>
<th>NATURAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MALE</td>
<td>FEMALE</td>
<td>MALE</td>
<td>FEMALE</td>
</tr>
<tr>
<td>$</td>
<td>F_0</td>
<td>$</td>
<td>14.9</td>
<td>14.3</td>
</tr>
<tr>
<td>$\sigma_{F_0}$</td>
<td>2.5</td>
<td>3.5</td>
<td>0.6</td>
<td>3.4</td>
</tr>
<tr>
<td>$\mu_{</td>
<td>F_0</td>
<td>}$</td>
<td>5.3</td>
<td>1.6</td>
</tr>
<tr>
<td>$\sigma_{</td>
<td>F_0</td>
<td>}$</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>$\mu_{\sigma_{</td>
<td>F_0</td>
<td>}}$</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$\mu_{\mu_{</td>
<td>F_0</td>
<td>}}$</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>$\mu_{\mu_{\mu_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>-1.2</td>
<td>-2.3</td>
</tr>
<tr>
<td>$\mu_{\sigma_{</td>
<td>F_0</td>
<td>}}$</td>
<td>1.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$\mu_{\sigma_{\sigma_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu_{\mu_{\sigma_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$\mu_{\sigma_{\mu_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu_{\sigma_{\sigma_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>$\mu_{\mu_{\mu_{</td>
<td>F_0</td>
<td>}}}$</td>
<td>16.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$\mu_{\sigma_{</td>
<td>F_0</td>
<td>}}$</td>
<td>53.7</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Regarding the standard deviations, we also note increased values for male TTS compared to natural speech. In contrast, the female standard deviations are often reduced. In comparison to natural speech, this indicates that $F_0$ modelling for female voices shares somewhat greater similarity across TTS systems than for male voices. Concerning the timing parameters $T_{va}$ and $\%V$, values for male and female signals are very similar. Increased $\sigma$ values for TTS indicate a broader range compared to natural speech.

5. Perceptual Modelling

The central question of this study is whether appropriate perceptual models could be constructed from the prosodic parameters introduced in Section 2. In answering this question we first analyse the relevance of core parameters within the quality space of the TTS database. Second, we apply sequential feature selection in combination with regression models to investigate the joint relationship between features and perceptual quality. Furthermore, cross-validation is adopted to give a realistic estimate of prediction accuracy rather than regressive fit. Finally, two experimental research lines are presented: These are (i) a reference mapping and (ii) a feature extension using second-order basis expansions. Pearson’s correlation coefficient $R$ is used as a measure of linear dependency between features, perceptual ratings, and predictions thereof.

5.1. Analysis of Quality Space

Table 3 gives the correlation coefficients between factor scores $y_i$ and selected features $x_i$, separately for each gender. Bold values are significant ($p < 0.05$).

<table>
<thead>
<tr>
<th>$x_i$</th>
<th>MALE</th>
<th>FEMALE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$y_1$</td>
<td>$y_2$</td>
</tr>
<tr>
<td>$\Delta F_0$</td>
<td>0.58</td>
<td>0.34</td>
</tr>
<tr>
<td>$\sigma F_0$</td>
<td>0.54</td>
<td>0.19</td>
</tr>
<tr>
<td>$F_0$</td>
<td>0.45</td>
<td>0.18</td>
</tr>
<tr>
<td>PR</td>
<td>0.76</td>
<td>0.21</td>
</tr>
<tr>
<td>DR</td>
<td>0.71</td>
<td>0.27</td>
</tr>
<tr>
<td>VR</td>
<td>0.74</td>
<td>0.15</td>
</tr>
<tr>
<td>$T_{va}$</td>
<td>-0.43</td>
<td>0.07</td>
</tr>
<tr>
<td>$%V$</td>
<td>-0.56</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 3: Correlations between features and factor scores.

The interpretation is as follows: For both genders most features show a marked relationship with the first factor (naturalness). Regarding the pure $F_0$ parameters, the positive correlation ($R > 0$) most likely reflects the negative perceptual impact of lacking $F_0$ dynamics in TTS as documented in Table 2. No significant correlation appears with the second factor. Concerning the third factor, significant cross-correlations are notable especially for DR, PR and VR. However, this applies only for the male stimuli, where a reasonable number of low-quality stimuli with temporal distortions also share intonational deficits. This is not the case for the female stimuli. In turn, timing parameters $T_{va}$ and $\%V$ correlate negatively. The marked correlations with factor 3 (temporal distortions) reflect the effect of polyphony (impression of multiple voices) [5] which can be caused by unnatural variations in speed, lacking speech pauses, and their lengths. Thus, perceptual categories like prosodic punctuation or spoken legato load on factors 1 and 3. In summary, these results suggest the interpretation of naturalness as a foremost prosodic quality dimension. This is also in line with high factor loadings on suprasegmental attributes such as accentuation and rhythm, as reported in [5].

5.2. Reference Mapping

An intuitive way of modelling the naturalness gap between TTS and natural speech is to apply a reference mapping of the features. This provides for the assumption of an “internal” reference of natural speech that the listening test subjects use unconsciously when rating speech quality. In the scope of this study, 2 classical magnitude mappings are considered:

$$X_{map,lin} = |X - X_{ref}|, \quad X_{map,log} = \log \frac{|X|}{X_{ref}}.$$  \hfill (6)

The reference matrix $X_{ref}$ comprises the per-gender means for natural speech (see Table 2). In the following all features are normalised using a modified z-score:

$$X_{norm} = \frac{X - X_{\mu}}{\sigma}, \quad \mu_{norm}.$$  \hfill (7)

The arbitrary target mean of all features $\mu_{norm}$ is set to 10. Matrix divisions in (6) and (7) are realised element-wise.

5.3. Feature Expansion

A controlled shift towards nonlinear feature combination is performed by expansion of the raw feature matrix $X$ [11]:

$$\tilde{X} = (h_1(X)\tilde{X})_{\lambda=1}.$$  \hfill (8)

Basis expansion functions $h_\lambda(X)$ are chosen as:

$$h_1(X) = X, \quad h_2(X) = x_i \cdot x_{ij}, \quad h_3(X) = \frac{x_i}{x_{ij}}.$$  \hfill (9)

Function $h_1$ simply reproduces the input matrix. Functions $h_2$ and $h_3$ denote the construction of cross products and cross divisions of all features, respectively.

5.4. Cross-Validated Feature Selection

Repeated sequential feature selection is used in connection with $K$-fold cross-validation [11, 9] as follows: For each trial $m$, a random partitioning of the $N$ observations into $K$ disjoint subsets is performed. Forward selection is conducted using the $K$ training sets $T_{\lambda}^{(k)}$ of size $N \cdot (1 - 1/K)$. The $k$-th test sets of size $N / K$ are denoted as $T_i^{(k)}$. For each temporary feature set $F_m \subset X$, a linear least squares regression model, acting as a composite quality estimator, is evaluated:

$$\hat{y} = \tilde{f}_m(\tilde{X}) = \hat{\beta}_0 + \sum_{j=1}^{J} \hat{\beta}_j \tilde{x}_j, \quad \tilde{x}_j \in F_m.$$  \hfill (10)

This model delivers estimated auditory ratings $\hat{y}$ from $\tilde{X}$ by using a subset of $J$ predictors $\tilde{x}_j$, weighted by scalar coefficients $\hat{\beta}_j$. The correlation $R_{mn}$ (regressive fit) serves as selection criterion to be maximized across the $K$ partitions,

$$R_{mn}(y, \tilde{f}_m) = \frac{1}{K} \sum_{k=1}^{K} R \left( y^{(k)}, \tilde{f}_m(\tilde{X}^{(k)}) \right),$$  \hfill (11)

where $y^{(k)}$ and $\tilde{X}^{(k)}$ denote the training sets according to $T_{\lambda}^{(k)}$. Features are added to form improved temporary models $\tilde{f}_m$ as...
The experiments, we take the naturalness scores as target vari-
ables. Rather, it seems appropriate to regularise principally
outliers. (e.g., PR

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strumental assessment of prosodic quality for text-to-speech sig-


Table 4: Figures of merit of composite quality estimators for
different feature sets, applied on test data partitions (3-fold
cross-validation).

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Feature} & \text{MALE} & & \text{FEMALE} & \\
\hline
\hline
\text{X} & \overline{R}_m^{(CV)} & \sigma \overline{R}_m^{(CV)} & \tau_m & \overline{R}_m^{(CV)} & \sigma \overline{R}_m^{(CV)} & \tau_m \\
\hline
h_{1}(X) & 0.83 & 0.05 & 0.16 & 0.79 & 0.07 & 0.20 \\
h_{1,3}(X) & 0.83 & 0.10 & 0.17 & 0.81 & 0.07 & 0.20 \\
X_{map,log} & 0.82 & 0.04 & 0.16 & 0.75 & 0.08 & 0.22 \\
X_{map,lin} & 0.74 & 0.09 & 0.20 & 0.59 & 0.15 & 0.28 \\
\hline
\end{array}
\]

• Prosodic variation systematically influences perceptual
naturalness of TTS signals and imposes a major impact
on their overall perceptual quality.

• \( F_0 \) dynamics are substantially lower in TTS than in nat-
ural speech.

• Prosodic features can be used to construct robust linear
models of perceptual quality.

• \( F_0 \)-specific quality differences between TTS signals
could be better modelled without a natural reference
mapping.

For future work, we envisage the exploration of robust acous-
tical parameters, suitable for a numerical description of ad-
tional quality factors in TTS, for example the naturalness of
voice and articulation. Hence, a full objective account of TTS
quality could be implemented.

7. Conclusions

In this paper, doors towards robust instrumental quality evalua-
tion of TTS signals have been opened. In particular, it has been
shown that formal prosodic parameters, derived from \( F_0 \) only,
enable the prediction of perceptual naturalness ratings with a
Correlation of up to 0.83 which explains nearly 70% of the ra-
ting variance. The essential conclusions are:

\[
\begin{align*}
\overline{R}_m^{(CV)}(y, \hat{f}_m) &= \frac{1}{K} \sum_{k=1}^{K} R \left( y^{(k)} - \hat{f}_m(\hat{X}^{(k-1)}) \right). \\
\epsilon_m(y, \hat{f}_m) &= \frac{1}{K} \sum_{k=1}^{K} \frac{K}{N} \left| y^{(k)} - \hat{f}_m(\hat{X}^{(k-1)}) \right|.
\end{align*}
\]

The \( k \)-th test set according to \( \hat{r}_m^{(k)} \) are denoted as \( y^{(k)} \) and \( \hat{X}^{(k-1)} \). The normalised root-mean-square error \( \epsilon_m \) is given by:

\[
\epsilon_m(y, \hat{f}_m) = \frac{1}{K} \sum_{k=1}^{K} \sqrt{\frac{K}{N} \left| y^{(k)} - \hat{f}_m(\hat{X}^{(k-1)}) \right|}.
\]

Functions max(\( y \)) and min(\( y \)) give the maximum and the min-
imum element of \( y \), respectively. These measures reflect the ro-
biteness of the composite model of trial \( m \). Overall, \( M = 500 

trials are carried out which ensures sufficient convergence for
the case of \( N = 30 \) and \( K = 3 \), applicable in this study. For
the experiments, we take the naturalness scores as target vari-
able, i.e., \( y = y_1 \). Figures of merit are the mean correlation
\( \overline{R}_m^{(CV)} \), the standard deviation \( \sigma \overline{R}_m^{(CV)} \), and the averaged root-
mean-square error \( \tau_m \).

6. Results and Discussion

Table 4 gives a performance overview of the different feature
matrices. It is noted that the use of the “raw” feature matrix \( \hat{X} \)
already yields cross-validated correlations in the range of 0.8,
which is considered as an excellent value taking into account
the ambiguity of speech prosody. A slight improvement can
be realised by including extra rhythm parameters [9]. Turning
to the feature expansion using \( h_1, h_2 \), and \( h_3 \), a somewhat im-
proved correlation for the female stimuli is noted. However,
for the male stimuli greater instability of the predictions (in-
creased \( \sigma \overline{R}_m^{(CV)} \)) indicates possible risks of nonlinear extensions.
The result shows that linear superposition of the proposed fea-
tures already does a good job as no striking information gain is
exposed through consideration of second order feature interac-
tions. Following an additional manual inspection of all features,
we see no indication for systematic nonlinearities which could be
modelled (e.g., by polynomials) for the benefit of substantial
improvements of prediction accuracy. Comparing the two ref-
ence mappings, the logarithmic mapping clearly outperforms
the linear mapping. However, no improvement can be recorded
compared to the usage of no mapping. We see the main reason
for this result in the remarkable prosodic difference between
TTS signals and natural speech signals. The feature values of
natural speech are rarely reached by most of the TTS signals.
Furthermore, the listening test comprised TTS signals only. At
this stage, we conclude that the differences between TTS sig-
als could be better modelled without consideration of a natural
reference. Rather, it seems appropriate to regularise principally
unbounded features, such as the mean \( F_0 \) slope, to a fixed range
(e.g., \( PR \in [0, 1] \)). This effectively helps to compensate for
outliers.