THE SPECTRAL RELEVANCE OF GLOTTAL-PULSE PARAMETERS

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ABSTRACT

The paper analyses how variations of the parameters of the Liljencrants-Fant (LF) model of glottal flow influence the speech spectrum, in order to determine the spectral relevance of these parameters. The effects of small parameter variations are described analytically. This analysis also gives an indication to what extent the LF parameters can be estimated reliably from the speech spectrum. The effects of larger parameter variations are discussed with the help of figures. Results are presented for a number of sets of estimated glottal-pulse parameters that were taken from the literature. The main conclusion is that the LF model, which, given the fundamental period, is a three-parameter model, actually operates as a one- or a two-parameter model.

1. INTRODUCTION

The glottal-flow characteristics during voicing, such as the open quotient, are often derived from a spectral representation of a segment of speech, e.g. [1, 2, 3]. This is done in order to avoid the difficulties of glottal-pulse parameter estimation by inverse filtering and subsequent waveform matching, often requiring manual fine-tuning. It was also for this reason that the author developed an algorithm, presented in [4], to estimate the parameters of the Liljencrants-Fant (LF) model of the glottal pulse [5] from the harmonic magnitude spectrum. The estimates turned out to be sensitive to small deviations of the harmonic spectrum due to noise or spectral estimation errors. This observation led to the analysis of the spectral relevance of the LF parameters presented here, which also explains the observed sensitivity to spectral errors. The analysis is also important for speech synthesis, because it shows how and to what extent the glottal-pulse parameters contribute to the magnitude spectrum, which mainly determines the perceptual impression of the speech.

Although the analysis is presented for the LF model and the mean-squared log-spectral distance is used to quantify the spectral changes, it can also be presented for other glottal-pulse models such as the Rosenberg model [6] or the R++ model [7] and other spectral-distance measures.

The outline of this paper is as follows. Section 2 discusses the LF model and presents the analysis method. The analysis is performed on a number of sets of estimated glottal-pulse parameters that were taken from the literature. These parameters and the results of the analysis are presented in Section 3. Section 4 presents a discussion and further work.

The main conclusion is that the LF model, which, given the fundamental period T_0, is a three-parameter model, actually operates as a one- or a two-parameter model. This means that certain parameter variations have hardly any effect on the spectrum and it explains that small changes in the measured spectrum can have strong effects on the estimated parameters.

2. ANALYSIS METHOD

A common production model for voiced speech is a source producing the time derivative of the glottal flow that excites a filter modeling the vocal-tract transfer function. The LF model is a standard model for the glottal-flow time derivative. An example of one cycle of the glottal-flow time derivative according to the LF model is shown in Figure 1. Its length is $T_0 = 1/f_0$, with f_0 the fundamental frequency. The waveform is given by an exponentially growing sine wave, until the instant of excitation T_e. The glottal flow reaches it maximum at T_p, when the time derivative changes sign. The instant of excitation T_e marks the first contact of the vocal folds at the beginning of glottal closure. Glottal closure completes in a short time, called the return phase. This is modeled as an exponential decrease of the time derivative. The return phase is often approximated by the time constant T_a of the exponential decay. The just presented T parameters are shown in Figure 1. They are specification parameters from which the generation parameters [5] must be derived. This involves solving a non-linear equation which is discussed in, e.g., [5] and [7]. The glottal-pulse time derivative with T parameters is denoted by $\dot{g}_\mathrm{T}(t; T_0, T_\mathrm{e}, T_\mathrm{p}, T_\mathrm{a})$, $0 \le t < T_0$. In this paper a related set of specification parameters, the R parameters, is used. They are: the open quotient (OQ), further denoted by $r_\mathrm{o} = T_\mathrm{e}/T_0$, the inverse speed quotient $r_\mathrm{k} = (T_\mathrm{e} - T_\mathrm{p})/T_\mathrm{e}$, and the relative return phase $r_\mathrm{a} = T_\mathrm{a}/T_0$. Given T_0, the LF model is fully specified by r_o, r_k and r_a. The glottal-pulse time derivative with R parameters is denoted by $\dot{g}_\mathrm{R}(\tau; r_\mathrm{o}, r_\mathrm{k}, r_\mathrm{a}) = \dot{g}_\mathrm{T}(\tau T_0; T_\mathrm{o}, r_\mathrm{o} T_0, (1 - r_\mathrm{k}) r_\mathrm{o} T_0, r_\mathrm{a} T_0)$, $0 \le \tau < 1$.

The harmonic of the glottal-pulse time derivative at frequency $l \times f_0$ has strength

$$H_l(\underline{r}) = \left| \int_0^1 \dot{g}_\mathrm{R}(\tau; r_\mathrm{o}, r_\mathrm{k}, r_\mathrm{a}) \mathrm{e}^{-\mathrm{j}2\pi l \tau} \mathrm{d}\tau \right|^2 . \qquad (1)$$

with $\underline{r} = (r_\mathrm{o}, r_\mathrm{k}, r_\mathrm{a})'$ a parameter vector. The prime symbol denotes vector or matrix transposition. The number of harmonics in digital speech is limited by $l < f_\mathrm{s}/(2f_0)$, with f_s the sampling frequency. The maximum number of harmonics is denoted by L. An expression for the outcome of the integral in (1) is given in [3]. Harmonic magnitude spectra will be denoted as column vectors, e.g. $\underline{H}(\underline{r})$ has elements $H_l(\underline{r})$ and will be power normalized, i.e. for any $\underline{r}$: $\sum_{l=1}^{L} H_l(\underline{r}) = 1$.

In order to investigate the spectral relevance of the R parameters, we study the effects of a small variation $\underline{\rho}$ of $\underline{r}$ on the $H_l(\underline{r})$,

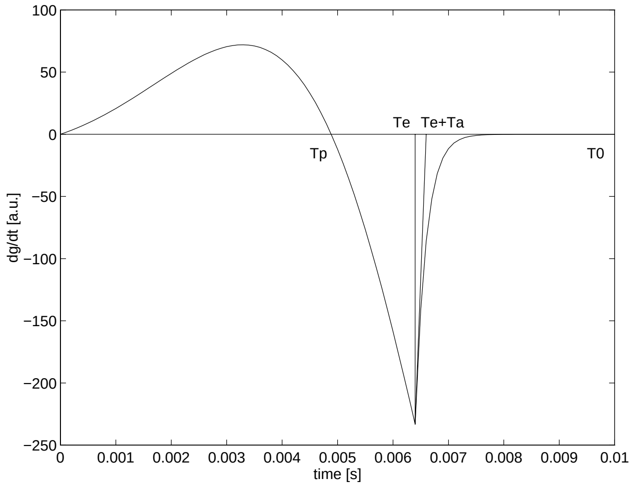

Figure 1: Glottal-pulse time derivative in arbitrary units according to the LF model.

which are quantified by means of the mean-squared log-spectral distance

$$D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r})) = \frac{1}{L}\sum_{l=1}^{L}\left|\ln(\frac{H_l(\underline{r}+\underline{\rho})}{H_l(\underline{r})})\right|^2. \quad (2)$$

Spectral differences are commonly expressed in decibels, in which case we consider $10\sqrt{D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r}))}/\ln(10)$. For $\underline{\rho} \ll 1$ we use the following second-order approximation

$$D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r})) = \frac{1}{2}\underline{\rho}'Q_{\underline{\rho}\underline{\rho}}(\underline{r})\underline{\rho}, \quad (3)$$

with $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ the positive-definite 3×3 matrix of second-order derivatives of (2) with respect to the elements of $\underline{\rho}$ at $\underline{\rho}=0$. Let $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$ denote the eigenvalues of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ and $\underline{u}_1, \underline{u}_2, \underline{u}_3$ the corresponding orthonormal eigenvectors, then (3) can be written as

$$D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r})) = \frac{1}{2}(\lambda_1|\underline{v}_1|^2 + \lambda_2|\underline{v}_2|^2 + \lambda_3|\underline{v}_3|^2), \quad (4)$$

with $\underline{v}_1$ the component of $\underline{\rho}$ in the direction of $\underline{u}_1$, etc.. We see that the spectral relevance of the glottal pulse parameters is determined by the eigenstructure of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$. For instance, if λ_3 is small, then a variation of $\underline{r}$ in the direction of $\underline{u}_3$ will only have a small effect on the harmonic magnitude spectrum.

We can now explain that the sensitivity to spectral errors of a glottal-pulse parameter estimation method based on minimizing the mean-squared log-spectral distance also depends on the eigenstructure of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$. The estimation method selects the parameter vector $\underline{r}$ which minimizes

$$D(\underline{H}(\underline{r}),\underline{G}) = \frac{1}{L}\sum_{l=1}^{L}\left|\ln(\frac{H_l(\underline{r})}{G_l})\right|^2, \quad (5)$$

with $\underline{G}$ the power-normalized harmonic magnitude spectrum estimated after inverse filtering. If the elements of $\underline{G}$ satisfy (1) except for a small additive spectral error $\underline{\Gamma}$, which may be an inverse-filtering error, an error due to noise or a model error, we can approximate (5) in a neighborhood of $\underline{r}$ by

$$D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r})+\underline{\Gamma}) = \quad (6)$$

$$\frac{1}{2}\underline{\rho}'Q_{\underline{\rho}\underline{\rho}}(\underline{r})\underline{\rho} + \frac{1}{2}\underline{\Gamma}'Q_{\underline{\Gamma}\underline{\Gamma}}(\underline{r})\underline{\Gamma} + \underline{\rho}'Q_{\underline{\rho}\underline{\Gamma}}(\underline{r})\underline{\Gamma},$$

with $Q_{\underline{\Gamma}\underline{\Gamma}}(\underline{r})$ the $L\times L$ second-order derivative matrix of $Q(\underline{r},\underline{\rho})$ with respect to $\underline{\Gamma}$ and $Q_{\underline{\rho}\underline{\Gamma}}(\underline{r})$ the $3\times L$ second-order derivative matrix of $Q(\underline{r},\underline{\rho})$ with respect to $\underline{\Gamma}$ and $\underline{\rho}$. The quantities $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ and $Q_{\underline{\rho}\underline{\Gamma}}(\underline{r})$ can be expressed in terms of the elements of $\underline{H}(\underline{r})$ and their derivatives with respect to $\underline{r}$. A nonzero $\underline{\Gamma}$ introduces an error in the estimated parameter vector that is given by

$$\Delta\underline{r} = -Q_{\underline{\rho}\underline{\rho}}(\underline{r})^{-1}Q_{\underline{\rho}\underline{\Gamma}}(\underline{r})\underline{\Gamma} = \frac{w_1}{\lambda_1}+\frac{w_2}{\lambda_2}+\frac{w_3}{\lambda_3}, \quad (7)$$

with $\underline{w}_1$ the component of $-Q_{\underline{\rho}\underline{\Gamma}}(\underline{r})\underline{\Gamma}$ in the direction of $\underline{u}_1$, etc.. This shows that a substantial error in the parameter estimates may occur in the directions of the associated eigenvectors, if one or more of the eigenvalues of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ are small.

So far, we have shown that the spectral relevance of glottal-pulse parameters and the robustness of spectral estimation methods for glottal-pulse parameters depend on the eigenstructure of a matrix $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$. In the next section we will compute the eigenvalues and -vectors of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ for various sets of LF parameters and discuss the relevance of these parameters to the spectrum.

3. RESULTS

The eigenvalues and eigenvectors of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ are computed for 27 glottal-pulse parameter sets taken from the references [8] and [9]. For each $\underline{r}$, $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$ was obtained by fitting a second order approximation to the set $\{D(\underline{H}(\underline{r}+\underline{\rho}),\underline{H}(\underline{r}))|\underline{\rho}\in\{-1,0,1\}^3\times 10^{-4}\}$. The number of harmonics was given by $L = 40$, but the results do not change much if this number is reduced to 10. The relative approximation error was 0.25% on average and maximally 0.44%. The R parameters and the eigenvalues and eigenvectors are shown in Table 1, ordered with increasing $r_{\rm a}$.

The R parameter $r_{\rm o}$ has a tendency to increase with $r_{\rm a}$, as was also observed in [10]. There is also a strong tendency of the maximum eigenvalue (or of the sum of the eigenvalues) to decrease with increasing $r_{\rm a}$ and $r_{\rm o}$. This means that the significance of all parameters to the spectrum decreases with increasing $r_{\rm a}$ and $r_{\rm o}$. We compare the effects on the harmonic magnitude spectrum of small R-parameter variations in the directions $\underline{u}_2$ and $\underline{u}_3$ with effects of variations in the (most significant) direction $\underline{u}_1$. We express the effects in decibels and, therefore, consider $\sqrt{\lambda_2/\lambda_1}$ and $\sqrt{\lambda_3/\lambda_1}$ rather than λ_2/λ_1 and λ_3/λ_1.

We first consider the entries 1–22, which contain the lower values of $r_{\rm a}$ and $r_{\rm o}$. The eigenvector $\underline{u}_1$ nearly always corresponds to a variation in the $r_{\rm a}$ direction, $\underline{u}_2$ to a variation in the $r_{\rm o}$ direction and $\underline{u}_3$ to a variation in the $r_{\rm k}$ direction. The only exception is entry 2, which shows an interchanged behaviour of $\underline{u}_2$ and $\underline{u}_3$ and has a larger $r_{\rm o}$ than its neighbors. The ratios $\sqrt{\lambda_2/\lambda_1}$ ('o') and $\sqrt{\lambda_3/\lambda_1}$ ('+') are plotted in Figure 2 as functions of $r_{\rm a}$ for all table entries. The entries 1–22 correspond to $r_{\rm a} < 0.075$. The separation line $r_{\rm a} = 0.075$ is indicated in the figure. The effect of a variation in the $\underline{u}_3$ direction on the harmonic magnitude spectrum is almost constant and on average about 1.7% of the effect of a variation with the same strength in the $\underline{u}_1$ direction. The largest effect is about 5% of the effect of a variation in the $\underline{u}_1$ direction. This is found for entry 18, which has a larger $r_{\rm o}$ than its neighbors. It follows for this subset that $r_{\rm a}$ has the highest spectral significance, that the spectral significance of $r_{\rm o}$ increases with increasing

Table 1: Glottal-pulse parameters and eigenvalues and eigenvectors of $Q_{\underline{\rho}\underline{\rho}}(\underline{r})$.

	r_{a}	r_{k}	r_{o}	λ_1 $[10^4]$	λ_2 $[10^4]$	λ_3 $[10^4]$	$\underline{u}_1'$			$\underline{u}_2'$			$\underline{u}_3'$		
1	0.01	0.25	0.25	4.1609	0.0023	0.0002	1.00	0.03	0.02	-0.04	0.56	0.83	-0.01	0.83	-0.56
2	0.01	0.29	0.63	3.5545	0.0010	0.0001	1.00	0.03	0.01	-0.03	0.92	0.40	0.00	-0.40	0.92
3	0.01	0.40	0.41	2.5356	0.0076	0.0004	1.00	0.04	0.02	-0.02	0.03	1.00	-0.04	1.00	-0.03
4	0.01	0.33	0.68	1.9531	0.0010	0.0004	1.00	0.05	0.01	-0.03	0.38	0.92	-0.04	0.92	-0.38
5	0.01	0.45	0.56	2.1451	0.0109	0.0005	1.00	0.05	0.02	-0.02	0.01	1.00	-0.05	1.00	-0.01
6	0.02	0.38	0.49	1.9067	0.0068	0.0003	1.00	0.05	0.02	-0.02	0.02	1.00	-0.05	1.00	-0.02
7	0.02	0.45	0.57	1.5811	0.0169	0.0004	1.00	0.06	0.01	-0.01	0.00	1.00	-0.06	1.00	0.00
8	0.02	0.51	0.65	1.6228	0.0260	0.0005	1.00	0.06	0.02	-0.02	0.00	1.00	-0.06	1.00	0.00
9	0.02	0.38	0.54	1.4043	0.0063	0.0003	1.00	0.06	0.02	-0.02	0.02	1.00	-0.06	1.00	-0.02
10	0.02	0.31	0.64	1.2146	0.0013	0.0003	1.00	0.06	0.02	-0.02	0.11	0.99	-0.06	0.99	-0.11
11	0.03	0.34	0.71	0.9549	0.0031	0.0002	1.00	0.07	0.02	-0.02	0.03	1.00	-0.07	1.00	-0.03
12	0.03	0.43	0.61	0.9935	0.0226	0.0002	1.00	0.07	0.02	-0.02	0.00	1.00	-0.07	1.00	0.00
13	0.03	0.41	0.69	0.9031	0.0123	0.0002	1.00	0.07	0.01	-0.02	0.00	1.00	-0.07	1.00	0.00
14	0.03	0.49	0.65	0.8444	0.0598	0.0003	1.00	0.08	0.03	-0.03	-0.01	1.00	-0.08	1.00	0.00
15	0.03	0.50	0.71	0.7627	0.0660	0.0002	1.00	0.09	0.03	-0.02	0.00	1.00	-0.09	1.00	0.00
16	0.04	0.51	0.68	0.6318	0.1167	0.0002	0.99	0.11	0.05	-0.05	-0.01	1.00	-0.11	0.99	0.01
17	0.04	0.48	0.71	0.4874	0.1028	0.0001	0.99	0.12	0.03	-0.03	-0.01	1.00	-0.12	0.99	0.00
18	0.04	0.44	0.89	0.2294	0.0041	0.0006	0.98	0.15	-0.09	0.11	-0.11	0.99	-0.14	0.98	0.12
19	0.05	0.51	0.65	0.4681	0.2495	0.0002	0.98	0.13	0.12	-0.11	-0.02	0.99	-0.13	0.99	0.00
20	0.05	0.52	0.71	0.3919	0.2817	0.0001	0.98	0.15	0.12	-0.11	-0.02	0.99	-0.15	0.99	0.00
21	0.05	0.42	0.76	0.2885	0.0485	0.0002	0.99	0.15	0.02	-0.02	0.00	1.00	-0.15	0.99	0.00
22	0.07	0.42	0.68	0.1919	0.1569	0.0001	0.93	0.20	0.32	-0.31	-0.07	0.95	-0.21	0.98	0.00
23	0.08	0.48	0.79	0.1465	0.0883	0.0005	-0.27	-0.09	0.96	0.91	0.30	0.28	-0.31	0.95	0.00
24	0.10	0.31	0.87	0.2326	0.0233	0.0008	-0.05	-0.04	1.00	0.84	0.55	0.06	-0.55	0.84	0.01
25	0.10	0.45	0.84	0.0414	0.0073	0.0010	-0.79	-0.44	0.42	0.42	0.12	0.90	-0.45	0.89	0.09
26	0.11	0.57	0.81	0.5502	0.0531	0.0017	-0.03	-0.03	1.00	0.82	0.56	0.04	-0.56	0.83	0.00
27	0.13	0.35	0.77	0.0258	0.0005	0.0001	-0.74	-0.62	0.28	-0.68	0.66	-0.32	-0.01	0.43	0.90

r_{a} and that the spectral significance of r_{k} remains at a constant low level. The decision whether the LF model operates as a one-, two- or three-parameter model in this r_{a} range depends on a threshold for the eigenvalue ratios. If we make an (arbitrary) choice for this threshold of 10%, then we find that the LF model operates as a one-parameter model for all entries with $r_{\mathrm{a}} < 0.019$ and as a one- or two- parameter model for the entries with $0.019 \leq r_{\mathrm{a}} < 0.075$.

The entries 23–27 show a different, less consistent, behaviour. The values of r_{a} and r_{o} are higher than in the entries 1–22. The eigenvectors are not systematically in the direction of one specific R parameter, but the $\underline{u}_3$s are moving about in a plane orthogonal to r_{o}, except for entry 27. Figure 2 shows that the $\sqrt{\lambda_2/\lambda_1}$ tend to decrease with increasing r_{a}, and that the $\sqrt{\lambda_3/\lambda_1}$ have increased somewhat compared with the entries 1–22. It seems that, although the total influence of the R parameters on the harmonic spectrum has decreased, the LF model operates more as a two- or (occasionally) even as a three-parameter model. More data in this r_{a} region are required in order to better detect tendencies and to justify more definite statements.

The above analysis is local, in the sense that it is only valid for small deviations $\underline{\rho}$ of $\underline{r}$. For larger deviations the situation is different. This is illustrated by Figure 3, which shows three plots of $D(\underline{H}(\underline{r}), \underline{H}(\underline{r}_{\mathrm{ref}}))$ with $\underline{r}_{\mathrm{ref}}$ equal to the R parameters in entry 15 of Table 1. In each plot only one of the R parameter is varied. Variations in the r_{a} and r_{k} directions appear to have a smooth monotonic effect on the mean-squared log-spectral distance, whereas the variation in the r_{o} direction has a more irregular effect, and the plot shows the presence of local minima, which hamper spectral parameter estimation. The sensitivity to a variation of r_{o} decreases

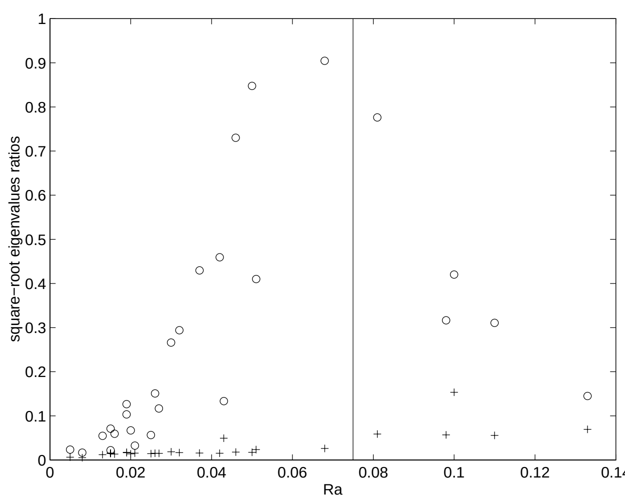

Figure 2: $\sqrt{\lambda_2/\lambda_1}$ ('o') and $\sqrt{\lambda_3/\lambda_1}$ ('+') as functions of r_{a}.

rapidly when r_{o} moves away from the optimum, say when $|r_{\mathrm{o}} - r_{\mathrm{o,opt}}| > 0.02$. Figure 4 shows 3-dimensional plots of the mean-squared log-spectral distance at a larger scale. The sharp dip in the bottom-left picture of Figure 3 is visible as a narrow valley in the bottom-left and top-right pictures of Figure 4. Outside this valley, the mean-squared log-spectral distance hardly depends on r_{o}. It is also rather insensitive to r_{k}. Further away from the optimum, the influence of r_{k} increases. This behaviour was observed for all table

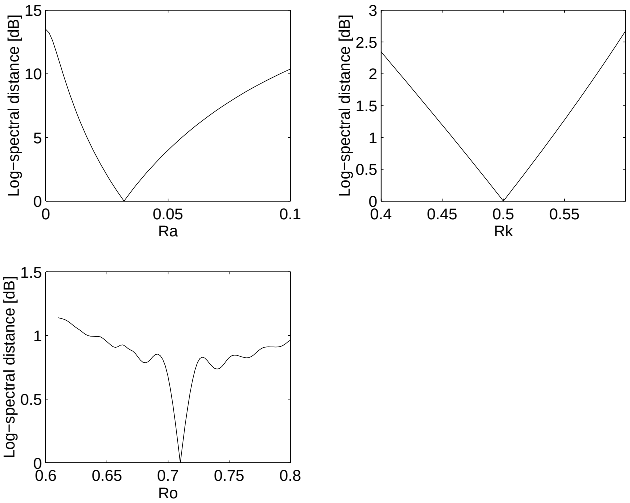

Figure 3: Mean-squared log-spectral distances [dB] for various parameter variations. Top left: constant $r_{\rm k}$, $r_{\rm o}$, top right: constant $r_{\rm a}$, $r_{\rm k}$, bottom left: constant $r_{\rm a}$, $r_{\rm k}$.

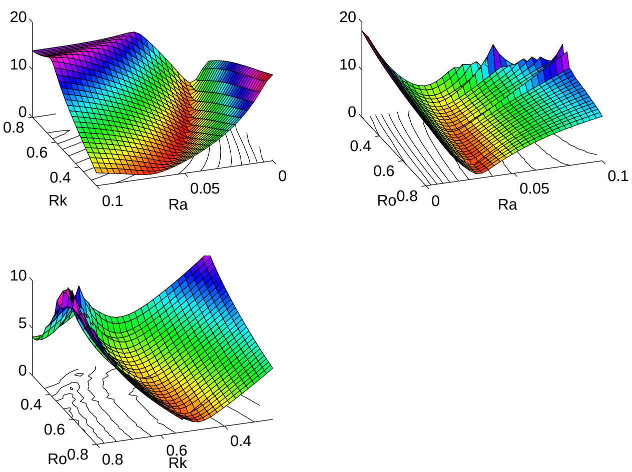

Figure 4: Three-dimensional plots of the mean-squared log-spectral distances [dB] for various parameter variations. Top left: constant $r_{\rm o}$, top right: constant $r_{\rm k}$, bottom left: constant $r_{\rm a}$.

entries 1–22.

4. DISCUSSION AND FURTHER WORK

Regarding the relevance of the R parameters of the LF glottal-pulse time derivative to the harmonic magnitude spectrum, we conclude that $r_{\rm a}$ has the highest spectral relevance. For $r_{\rm a} < 0.075$, we have observed that a difference in $r_{\rm k}$ only contributes to the spectral distance when it is large. A difference in $r_{\rm o}$ can become spectrally relevant, but only when glottal pulses are considered whose $r_{\rm o}$s are already close, say $|\Delta r_{\rm o}| < 0.02$. This type of local spectral relevance of $r_{\rm o}$ increases with increasing $r_{\rm a}$.

The spectral relevance of small variations of the R parameters have been analyzed in quantitive terms. The spectral relevance of larger deviations, however, could only be discussed in more qualitative terms. A next step is to try to derive tracks of maximal (or minimal) relevance. This could be done by making a small step, say with length $|\rho| = 0.001$, from a starting point into the $\underline{u}_3$ (or $\underline{u}_1$) direction, and then computing each next small step in the direction in which the mean-squared log-spectral distance changes maximally (or minimally) with respect to the starting point. From these tracks we can compute, for instance, the point that gives a mean-squared log-spectral error of 1 dB in the direction of maximal (or minimal) spectral relevance.

We have considered the relevance of small deviations of the LF parameters to the harmonic magnitude spectrum, of which it is believed that it mainly determines the perceptual impression of speech. It would be interesting to apply the same type of analysis to a mean-squared distance in a loudness space, which would give a better founded indication of the perceptual difference between two sets of R parameters. This type of analysis is more complicated because, in stead of the the values of the harmonics H_l, it requires the values of the speech harmonics $H_l(\underline{r})|A({\rm j}2\pi l f_0)|^2$ which depend on the transfer function $A({\rm j}\omega)$ of a vocal-tract filter and which are f_0 dependent. However, it seems interesting to do this analysis, and to verify the results with a perceptual experiment in which just-noticable differences are measured along the tracks of maximal (or minimal) perceptual relevance.

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