



# Differentiable Time-Varying Linear Prediction in the Context of End-to-End Analysis-by-Synthesis

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## Abstract

Training the linear prediction (LP) operator end-to-end for audio synthesis in modern deep learning frameworks is slow due to its recursive formulation. In addition, frame-wise approximation as an acceleration method cannot generalise well to test time conditions where the LP is computed sample-wise. Efficient differentiable sample-wise LP for end-to-end training is the key to removing this barrier. We generalise the efficient time-invariant LP implementation from the GOLF vocoder to time-varying cases. Combining this with the classic source-filter model, we show that the improved GOLF learns LP coefficients and reconstructs the voice better than its frame-wise counterparts. Moreover, in our listening test, synthesised outputs from GOLF scored higher in quality ratings than the state-of-the-art differentiable WORLD vocoder.

**Index Terms:** speech synthesis, linear prediction, differentiable DSP, source-filter model, harmonic-plus-noise model

## 1. Introduction

Efficiency and interpretability are important aspects of neural voice synthesis. Instead of building high-quality but computationally expensive black-box vocoders [1, 2, 3, 4], efforts have been made to increase controllability and reduce computational complexity while retaining the same voice quality. One promising approach is utilising synthesis components in the classic source-filter framework to split the workload of neural networks and train them jointly [5, 6]. The filter in this framework represents the response of the vocal tract, which is often modelled using linear prediction (LP) based on the varying diameters tube model [7]. The LP coefficients (LPCs) are very compact features and require low transmission bandwidth.

Although LP has a long history in voice modelling [7], its recursive computation makes end-to-end training extremely slower than non-recursive filters due to the overhead for building deep computational graph [8]. LPCNet series [5, 9] address this problem by modelling the inverse filtered speech, thus utilising parallel computation. Several works parallelise LP by frame-wise processing and overlap-add [10, 11], while Yu et al. [8] accelerate it further with custom kernels for gradient backpropagation. Other works seek to approximate the vocal tract filter using FIRs [12, 13, 14, 15]. Besides LPCs, different filter representations have been explored as well, such as linear/mel-scale spectral envelope [14, 15] or cepstral coefficients [13, 16].

This paper proposes a new differentiable vocoder based on the GOLF vocoder [8]. We extend their custom backpropagation method to work with time-varying LP, removing mismatches between training and evaluation conditions with the cost of slightly slower training speed than frame-wise approxi-

mation. We conducted an end-to-end analysis-by-synthesis experiment and compared the performance of several differentiable components with two classic synthesiser formulations. We also compare the spectral envelopes of different methods' learnt LPCs.

## 2. Background

### 2.1. Harmonic-plus-noise GOLF

Global flow LPC Filter (GOLF) is a singing vocoder proposed by Yu et al. [8]. Given mel-spectrograms as conditions, a neural network encoder converts them into synthesis parameters, which are then passed to the decoder, also known as a synthesiser. The synthesiser has the following form:

$$S(z) = G(z)M(z) + N(z)C(z), \quad (1)$$

where  $S(z)$  is the voice signal which consists of  $G(z)$  the glottal pulses filtered by a LP filter  $M(z)$  and a white noise  $N(z) \sim \mathcal{N}(0, 1)$  controlled by another LP filter  $C(z)$ . This resembles the classic harmonic-plus-noise (HpN) model [17], which has been used in several related works [13, 14, 18] with different harmonics and noise components. GOLF generate  $G(z)$  using wavetable synthesis, where the wavetables are sampled from the transformed LP model [19] with different  $R_{L_j}$ .

### 2.2. Differentiable time-invariant LP

Although the response of the vocal tract varies from time to time in speech, we can assume it is invariant in a short time. Based on this assumption, the computation of the LP filter is given by

$$\begin{aligned} s(t) &= \text{LP}_a \{e(t)\} \\ &= e(t) - \sum_{i=1}^M a_i s(t-i), \end{aligned} \quad (2)$$

where  $s(t)$  is the time-domain speech signal,  $e(t)$  the excitation signal,  $\mathbf{a} = [a_1, \dots, a_M]$  the LP coefficients with a chosen order  $M$ .  $e(t)$  and  $s(t)$  are zero for  $t < 0$ . Yu et al. and Forgiato et al. [8, 20] show that given a loss function  $\mathcal{L}$  and the gradients  $\frac{\partial \mathcal{L}}{\partial s(t)}$ , the gradients  $\frac{\partial \mathcal{L}}{\partial e(t)}$  and  $\frac{\partial \mathcal{L}}{\partial a_i}$  can be computed as

$$\frac{\partial \mathcal{L}}{\partial a_i} = \sum_{t=0}^T \frac{\partial \mathcal{L}}{\partial s(t)} \text{LP}_a \{-s(t-i)\} \quad (3)$$

$$\frac{\partial \mathcal{L}}{\partial e(\mathcal{T}-t)} = \text{LP}_a \left( \frac{\partial \mathcal{L}}{\partial s(\mathcal{T}-t)} \right), \quad (4)$$

where  $\mathcal{T} + 1$  is the number of audio samples and  $\mathcal{T} - t$  means reverse indexing. As the computation only consists of

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**Jessica J Manson**



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