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Component isolation for multi-component signal analysis using a non-parametric gaussian latent feature model

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ABSTRACT

A challenge in analysing non-stationary multi-component signals is to isolate nonlinearly time-varying signals especially when they are overlapped in time and frequency plane. In this paper, a framework integrating time-frequency analysis-based demodulation and a non-parametric Gaussian latent feature model is proposed to isolate and recover components of such signals. The former aims to remove high-order frequency modulation (FM) such that the latter is able to infer demodulated components while simultaneously discovering the number of the target components. The proposed method is effective in isolating multiple components that have the same FM behavior. In addition, the results show that the proposed method is superior to generalised demodulation with singular-value decomposition-based method, parametric time-frequency analysis with filter-based method and empirical model decomposition base method, in recovering the amplitude and phase of superimposed components.

1. Introduction

In many applications encountered in practice, non-stationary multi-component signals consist of various non-linearly frequency-modulated (FM) components. The latter convey important information concerning the non-stationary process that assumedly generates the signals. A critical signal processing task is to isolate FM components, where this is complicated by the complex time-frequency structures of the signals; e.g., the micro-Doppler signatures of radar echo corresponding to components of moving target are intersected in time-frequency domain; the characteristic frequencies of rotatory machine and their harmonics are inseparable in frequency domain undergoing non-stationary operating process; the frequencies and harmonics of underwater mammal calls vary nonlinearly and are inseparable in frequency domain. In general, the isolated non-stationary components as important features are useful in both target/novelty detection, condition monitoring, etc.

Empirical mode decomposition (EMD) is known for decomposing a signal into a series of intrinsic mode functions (IMF) [6], each of which is assumed to be a mono-component. However, EMD is incapable of dealing with intersected components or broad-bandwidth nonlinear FM components. Filter- or mask-based methods in the time-frequency domain could cope with such components [1], though a substantial challenge is to determine bandwidth or masking size to capture local features. A trade-off of using filters or masks lies in recovering the intersected components; i.e., one is fully recovered while the other will be broken down and cannot be recovered at the point at which components cross. Widely-studied component

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separation methods such as the Hough transform [2], singular value decomposition [3], and energy separation [4] perform well in the case of intersected stationary components, though the number of the target components often needs to be defined in advance.

The non-parametric Gaussian latent feature model (NGLF) [12–16] is known for its capacity to infer latent features without prior knowledge. The components of a multi-component signal can be considered as being latent features of the signal; the NGLF thereby holds significant potential for improved component isolation. The NGLF is superior to independent component analysis [7–9] and non-negative matrix factorisation [10], which are two well-studied models for automatic component isolation, in the case that the number of the latent features is unknown. However, the latter methods assume that the latent feature is static in the observations, while time-frequency patterns of FM components vary with time. A challenge exists in how to apply the NGLF to the identification of FM components. A straightforward solution is to project the FM components into a space where the components are stationary so that the NGLF is able to resolve the latent features.

In this paper, we propose an integrated framework that combines (i) a time-frequency analysis-based demodulation and (ii) the NGLF. The demodulation technique assumes a frequency-modulated signal model with the phase modulating by a high-order function of time [17,18]. To acquire the parameters of an arbitrary phase function, we adapt the parametric time-frequency transform (PTFT) [5]. The latter was proposed as a time-frequency domain analysis method that is capable of using an arbitrary phase transform kernel to capture the local time-frequency pattern of a non-stationary signal, and to obtain a time-frequency representation with enhanced energy concentration. An iterative parameter estimation scheme associated with the PTFT provides the basis for demodulating various multi-component signals. *In [23], a combination of the PTFT and simple band-pass filter was applied for component extraction, though the filter resulted in attenuation at the edges of components and amplitude distortion at the cross-point between intersecting components. In [21], the PTFT was integrated with singular value decomposition (SVD), but we note that the SVD strongly relies on the accuracy of the estimation of the demodulation.* In addition, it can neither deal with multiple components with the same frequency modulation nor with local components. In [22], a joint-refinement post-processing step was used to recover the amplitude of intersected components, though it assumed that the component is known and the estimation for all components cannot reach the best simultaneously. The framework described in this paper provides alternative solutions to cope with the above limitations in component isolation. In the proposed framework, the PTFT aims to remove the high-order FM in components so that the NGLF is able to infer the demodulated components automatically without defining the number of the components. *It is shown that the proposed method is effective in isolating multiple components with the same FM behavior at one time.* In addition, the results show that the proposed method is superior to generalised demodulation with singular-value decomposition-based isolation, parametric time–frequency analysis with filter-based isolation and empirical model decomposition base isolation, in recovering the amplitude and phase of superimposed components.

The remainder of this paper is organised as follows: Section 2 introduces a signal model and the underlying principles of the NGLF and PTFT; Section 3 provides the details of the proposed framework and a demonstration on an exemplar signal. Section 4 provides analysis results of applying the proposed method with both simulated and experiment signals. Finally, Section 5 draw conclusions.

2. Theoretical background

2.1. Signal model

We assume a multi-component signal $S(t) \in \mathbb{R}^1$ with L components $s(t)$,

$$S(t) = \sum_{l}^{L} s_l(t) \tag{1}$$

with

$$s(t) = A(t)\exp\{-i\phi(t)\} \tag{2}$$

where $\sqrt{i} = -1$. $A(t)$ and $\phi(t)$ are time-varying amplitude and phase, respectively. Eq. (2) is an analytic form of signal components. Instantaneous frequency (IF) is a measurement of time-frequency pattern defined for non-stationary signal as,

$$IF(t) = \frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}t}\phi(t) \tag{3}$$

which assumes that the phase function $\phi(t)$ is differentiable. Noted that this definition is for mono-component signals, it is also valid for individual component of multi-component signals.

A signal with finite time support can be cast into a set of segments with overlap. For example, the multi-component signal $S(t)$ is divided into a set of overlapped segments with the length of D; i.e., $\mathbf{X} = \{x^{(1)}, \ldots x^{(N)}\}$, $x^i \in \mathbb{R}^D$.

We assume that a component set $\mathbf{A} = \{a^{(1)}, \ldots, a^{(K)}\}$, $a^j \in \mathbb{R}^D$ is responsible for generating the data $\mathbf{X}$,

$$\mathbf{X} = \mathbf{W}^T\mathbf{A} \tag{4}$$