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Analysis of multicomponent AM-FM signals using FB-DESA method

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ABSTRACT

The discrete energy separation algorithm (DESA) together with the Gabor's filtering provides a standard approach to estimate the amplitude envelope (AE) and the instantaneous frequency (IF) functions of a multicomponent amplitude and frequency modulated (AM-FM) signal. The filtering operation introduces amplitude and phase modulations in the separated monocomponent signals, which may lead to an error in the final estimation of the modulation functions. In this paper, we have proposed a method called the Fourier–Bessel expansion-based discrete energy separation algorithm (FB-DESA) for component separation and estimation of the AE and IF functions of a multicomponent AM-FM signal. The FB-DESA method does not introduce any amplitude or phase modulation in the separated monocomponent signal leading to accurate estimations of the AE and IF functions. Simulation results with synthetic and natural signals are included to illustrate the effectiveness of the proposed method.

1. Introduction

In the present work, we consider real multicomponent amplitude modulated (AM) and frequency modulated (FM) signals comprising of individual components of the form $A(t)\cos(\omega t + \phi(t))$ for analysis and synthesis [1]. The signal model finds application in speech analysis/synthesis where each formant of speech is represented by an individual AM-FM signal [2–6].

In the parametric approach of analysis of an AM-FM signal, the functions $A(t)$ and $\phi(t)$ are expanded in terms of some basis functions whose coefficients are to be determined [7,8]. In the nonparametric approach, an individual component is separated by band-pass filtering, and the time-varying amplitude and phase functions are estimated conveniently by the energy separation algorithm (ESA) [9].

It should be pointed out that the optimum choice of the center frequency and that of the bandwidth of the filter may be difficult when $\phi(t)$ is arbitrary. Moreover, a band-pass filtering process imposes amplitude and phase distortions in an isolated component leading to inaccurate estimations of the time-varying functions.

In this paper, we consider the non-parametric approach of signal analysis, where the amplitude and frequency functions are estimated by the discrete ESA (DESA) [3,9]. The main purpose of this work is to present a technique which will allow us to separate an AM-FM component of a multicomponent signal with out introducing any distortion in the amplitude or the phase of the separated channel. It is intended that the process of separation of all channels of the composite signal should be a one-step process [10], and the technique will need no prior information about the frequency-bands of the individual channels. In the sequel, we present a method based on the Fourier–Bessel (FB) expansion, which can separate the individual channels with all desirable properties.

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2. Multicomponent AM-FM signal and DESA

A real multicomponent AM-FM signal model is represented as [1]

$$x(t) = \sum_{i=1}^{M} A_i(t)\cos\big(\omega_i t + \phi_i(t)\big) \tag{1}$$

where the signal $x(t)$ comprises of M monocomponent signals $x_i(t)$ given by

$$x_i(t) = A_i(t)\cos\big(\omega_i t + \phi_i(t)\big) = A_i(t)\cos\big(\Phi_i(t)\big) \tag{2}$$

and $A_i(t)$ is the time-varying amplitude envelope (AE) of $x_i(t)$ at the ith channel with instantaneous frequency (IF)

$$\Omega_i(t) = \frac{d(\Phi_i(t))}{dt} = \omega_i + \frac{d\phi_i(t)}{dt} \tag{3}$$

Since the energy separation algorithm requires an additional task of separating the modulated signal at each channel before estimating the AE and the IF functions, the composite signal $x(t)$ is subject to band-pass filtering in the range of $\Omega_i(t)$.

The discrete-time version of a monocomponent signal band-pass filtered at the center frequency ω_c is given by

$$s(n) = A(n)\cos\big(\Phi(n)\big) \tag{4}$$

or expanding the phase term

$$s(n) = A(n)\cos\left(\omega_c n + \omega_m \int_0^n q(k)\,dk\right) \tag{5}$$

where ω_m is the maximum deviation of frequency from ω_c, and the sequence $q(n)$ is chosen such that $|q(n)| \leqslant 1$.

Both the instantaneous frequency (IF) and the amplitude envelope (AE) of an individual channel can be derived from the Teager's nonlinear energy-tracking operator. Using the algorithm formulated by Kaiser, the Teager-energy of the discrete signal $s(n)$ is calculated by the operator $\Psi(.)$ given by [9]

$$\Psi\big[s(n)\big] = s^2(n) - s(n-1)s(n+1) \tag{6}$$

From the energy operators of a signal and its time-shifted versions $r(n) = s(n) - s(n-1)$, the instantaneous frequency (IF) $\Omega(n)$, and the amplitude envelope (AE) $|A(n)|$ are calculated using the DESA [3,4] as

$$\Omega(n) \approx \cos^{-1}\left[1 - \frac{\Psi[r(n)] + \Psi[r(n+1)]}{4\Psi[s(n)]}\right] \tag{7}$$

$$\big|A(n)\big| \approx \sqrt{\frac{\Psi[s(n)]}{1 - (1 - \frac{\Psi[r(n)]+\Psi[r(n+1)]}{4\Psi[s(n)]})^2}} \tag{8}$$

In deriving (7), it is assumed that $0 \leqslant \Omega(n) \leqslant \pi$. Thus, the DESA method can estimate instantaneous frequency upto half of the sampling frequency.

The estimation errors of DESA method are practically negligible for the AM-FM signals with realistic values of modulation process, but the AE and IF estimation errors can be reduced further by using the smoothed energy signals. Smoothing can be applied on the estimated AE and IFs (post-smoothing) instead of the energy signals (pre-smoothing). Both approaches (post and pre-processing) yields similar results [4]. Note that the main source of errors in the estimations of the AE and IF functions of a multicomponent AM-FM signal is the band-pass filtering which, in effect, modulates the separated component of the signal [4].

3. Effects of band-pass filtering

Consider an AM-FM signal of the form (2)

$$x_i(t) = A_i(t)\cos\big(\omega_i t + \phi_i(t)\big) = A_{i1}(t)\cos(\omega_i t) - A_{i2}(t)\sin(\omega_i t) \tag{9}$$

where

$$A_{i1}(t) = A_i(t)\cos\big(\phi_i(t)\big), \qquad A_{i2}(t) = A_i(t)\sin\big(\phi_i(t)\big)$$

We filter $x_i(t)$ through a band-pass filter with impulse response $h_i(t) = h_{il}(t)\cos(\omega_i t)$, where $h_{il}(t)$ is the impulse response of the corresponding low-pass filter and ω_i is the carrier frequency of the AM-FM signal $x_i(t)$. Then, the filtered signal $s_i(t) = x_i(t) * h_i(t)$ will be given by [11]