Analysis and decomposition of frequency modulated multicomponent signals

PhD Thesis in Mathematical Models for Engineering

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Thesis Summary

Frequency modulated (FM) signals involve many research fields, including seismology, astrophysics, biology, acoustics, animal communication and echolocation, and also manmade systems, such as radar and sonar. Generally, an observed signal consists of the superposition of multiple waveforms and it is thus referred as multicomponent signal (MCS). Each mode has a specific time-dependent frequency content, known as instantaneous frequency (IF).

In many applications, the extraction of signal characteristics (i.e. amplitudes and IFs) is required, that is why MCS decomposition is an important topic in signal processing. It consists of the recovery of each individual mode and it is often performed by IFs separation. TF analysis can successfully reach the goal if modes are sufficiently apart in the TF plane, but the task becomes very challenging if signal modes overlap in the TF domain, i.e. they interfere with each other, at the so-called non-separability region. Unfortunately, a general solution to MCS decomposition is not available yet. As a matter of fact, existing methods for overlapping modes decomposition all have the same limitations: they are parametric —i.e. they adapt only to the assumed signal class, or they rely on signal-dependent and parametric TF representations— otherwise they are interpolation techniques—i.e. they almost ignore information corrupted by interference and recover IF curve by some fitting procedures, resulting in high computational cost and bad performances against noise.

This thesis aims at overcoming these drawbacks, providing efficient tools for dealing with MCS with interfering modes. It is composed of three chapters: Chapter 1 contains the mathematical tools needed to introduce the problem,

as well as an extended state-of-the-art revision. Chapter 2 and Chapter 3 are devoted to the results obtained during the Phd course and reflect two strategies: the former is an iterative approach that aims at enhancing MCS' resolution in the TF domain; the latter is a transform-based approach, that processes signal energy for separating individual modes. Spectrogram, i.e. the Short-Time Fourier Transform squared modulus, is adopted as underlying signal TF distribution (TFD) in this thesis.

Chapter 2 first presents the motivation of the work, by deeply discussing the problem of resolution loss in TF representations of overlapped modes. In fact, interference between modes generally causes IFs curves deviation in the TF domain, that prevents modes separation and correct IFs estimation—as a further effect, sparsification approaches such as reassignment method (RM) are unreliable in case of overlapping modes. A general spectrogram evolution law is then introduced to explain IFs curve deviation and to define the notion of weak separability. The latter allows for the definition of robust iterative methods, aimed at concentrating spectrogram distribution on IFs curves, by sequentially reallocating each TF point on the IF curve corresponding to the belonging mode. Convergence properties and discussions concerning methods conditioning are also included. As shown by the experimental results, despite of some negligible instabilities, the proposed iterative techniques provide sparse signal TF representations, with higher resolution properties with respect to RM, as well as a lower computation cost.

The transform-based approach combines TF analysis and energy-based transforms, specifically Radon Transform (RT). In Chapter 3, two important properties concerning signal energy are shown: the energy of a MCS still is a MCS, whose new IFs depend on the original ones; signal energy reveals the presence of interference, as it oscillates exactly at the non-separability regions. Based on these results, a STFT-based method for IFs recovery, at the non-separability region, is proposed. Experimental results are provided and compared to the ones given by standard RM. Chapter 3 also presents an energy-based method for the automatic non-separability region detection, that can be very useful in methods dealing with overlapping modes, as a pre-processing.

A further step is done by considering the combination of TF analysis and RT. Indeed, in case of crossing components, spectrogram RT provides a new signal representation, namely Radon Spectrogram Distribution (RSD), where modes appear discriminated. Motivated by this interesting property, a theoretical study concerning RSD of a monocomponent signal is provided and, in particular, IF curve is characterized in the Radon domain. The study allows to introduce a method for overlapping modes separation. Indeed, if signal amplitudes are comparable, thresholding RSD provides a partitioning into subdistributions, representing each individual components. IFs signatures can be thus extracted separately. Finally, the inversion of RT limited to IFs signatures provides separated IFs curves, as shown by numerical tests, performed on both deterministic and noisy synthetic signals. Contrary to existing strategies that ignore regions affected by interference and approximate the missing target by interpolation, the proposed one exploits all the available information in the TFD to separate IFs curves. Even though method accuracy slightly degrades at the TF boundaries, the presented approach is very promising and opens to new developments.

As main advantage, methods derived from both the iterative and the transform-based approaches are non-parametric, as they do not require specific assumptions on the signal class. Constant-amplitude synthetic MCS have been considered in the numerical tests, as they well model many real-life signals, such as radar signals with Doppler modulation, that are used in human-gait classification and in video surveillance. Experimental results have confirmed both the effectiveness of the proposed approach, with a consequent improvement of the state-of-the-art, and its potential in solving a challenging problem in TF analysis of FM-MCS. In particular, although MCS resolution has been improved significantly in TF non-separability regions, an additional effort is needed for applying the presented study to amplitude modulated MCS and non-monotonic IFs, which are recurrent features in real-world signals. Furthermore, even though the presented thesis focused on a specific TFD, namely spectrogram, study and results are expected to adapt to different TFDs, making the applicability to real-life signals more viable.