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瞬时频率估计及其应用研究

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本论文经答辩委员会全体委员审查，确认符合上海大学博士学位论文质量要求。

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答辩委员会对论文的评语

在许多实际的信号处理中，估计一个非平稳过程的瞬时频率是一项极为重要的工作，该论文从时频分布的角度对瞬时频率的估计方法及应用进行了研究，这对于丰富和发展瞬时频率的估计方法具有重要的理论和实用价值。

作者在对瞬时频率和时频分布的理论和应用进行系统和深入研究的基础上，开展了瞬时频率估计方法和应用的探索和研究。主要创新点如下：(1) 利用 WVD 核函数的共轭对称性和三角函数的周期性与对称性，实现了快速余弦运算与快速正弦运算，提高了 WVD 的计算速度。并且该算法可以采用"同址运算"方式实现，节省存储单元。(2) 证明了对线性调频的 AM-FM 信号，只要其幅度的 WVD 在 $f=0$ 处取得最大值对任意 t 成立，基于 WVD 谱峰检测得到的结果是无偏的，并给出了估计方差。(3) 揭示了在低信噪比下采用 XWVD 谱峰检测统计性能的优越性。(4) 提出采用高斯函数的分数阶傅立叶变换作为基函数的自适应时频扩展，利用相应的自适应时频分布的谱峰检测来估计信号瞬时频率，不仅有较好的抗噪声干扰的能力，而且可以灵活地处理多分量信号。

答辩委员会认为该论文立论正确，论证严格，试验数据详实可靠，结论可信。反映了作者很好地掌握了坚实宽广的理论基础和系统深入的专门知识，具有很强的独立科研能力。写作思路清楚，文笔流畅，达到了博士学位水平。答辩过程中阐述流畅，概念清楚，正确回答了评委的提问。经答辩委员会无记名投票，一致同意通过陈光化同学的博士学位论文答辩，并建议学位评定委员会授予其工学博士学位。

答辩委员会表决结果

答辩委员会以无记名投票，一致同意通过该生的博士论文答辩，并建议学位评定委员会授予陈光化同学工学博士学位。

答辩委员会主席：宋文涛

2002年1月21日

摘　要

瞬时频率是许多物理现象的定量描述，因此，把握了瞬时频率，便把握了这些现象的物理实质. 在实际的信号处理中，瞬时频率在雷达、声纳、移动通信等领域有着广泛地应用. 所以，研究瞬时频率的估计方法及各种方法的性能对国民经济的发展和国防建设有重要的意义. 时频分布可以在时频二维平面上给出信号的时变频谱，因此利用时频分布来分析和估计瞬时频率有助于更加深刻地理解瞬时频率的物理意义. 事实上，估计瞬时频率是二维时频分布的重要任务之一. 本文从时频分布的角度对瞬时频率的估计方法与应用进行了较为深入的研究.

本文首先给出了瞬时频率的定义和一些相关的概念，回顾了近年来瞬时频率估计的理论研究和应用发展概况，阐明了本文的研究目的、意义和内容.

接着，本文对 WVD 的快速计算进行了研究. 利用 WVD 核函数的共轭对称性，把 WVD 的计算从复数域变换到实数域，不但移去了计算冗余，而且使核函数的计算长度减少了一半. 利用三角函数的周期性与对称性，实现了快速余弦运算与快速正弦运算，大大提高了 WVD 的实现速度. 使计算 WVD 的计算量从 $2N\log2^{2N}-7N+6$ 次实数乘法和 $3N\log2^{2N}-3N+2$ 次实数加法减为 $(N/2)\log 2^{N}-N$ 次实数乘法和 $(2N-2)\log2^{N}-2N+2$ 次实数加法. 而且本文提出的算法有类似于快速傅立叶变换的蝶形单元，可以采用“同址运

算”方式实现，以节省存储单元. 与原来方法相比，本文提出的算法有明显的优越性.

第三章对应用 WVD 谱峰检测估计 AM-FM 信号的瞬时频率进行了研究. 研究结果表明：对线性调频的 AM-FM 信号，只要其幅度的 WVD 在 $f=0$ 处取得最大值对任意 t 成立，基于 WVD 谱峰检测得到的结果是无偏的. 在文中，用详细的推导给出了估计方差. 这一结果，扩展了应用 WVD 谱峰检测估计瞬时频率的使用条件. 仿真实验采用带高斯包络线性调频信号表明：在没有噪声干扰时，对四种幅度变化趋势的线性调频信号，在幅度满足条件的情况下，都能准确估计出信号的瞬时频率. 并且当幅度先递减后递增，且幅度变化率适中时，估计的统计性能优于常数幅度的统计性能. 这一结果对实际的信号处理，特别是对信号进行时频分析时，有积极的指导意义.

在第四章中，从 WVD 和 XWVD 的统计性能的角度解释了基于 XWVD 谱峰检测的瞬时频率估计结果的统计性能比基于 WVD 的估计结果的统计性能好得多的原因：即在噪声环境中，我们可以从计算得到的 XWVD 中估计出有用信号的 XWVD，估计结果是无偏的，估计的方差等于噪声的方差. 所以，应用 XWVD 谱峰检测可以在低信噪比下准确地估计出信号的瞬时频率. 但是，在噪声环境中，我们无法从计算得到的 WVD 中估计出有用信号的 WVD，更不用说估计出瞬时频率了. 仿真实验表明，对具有高斯调幅的线性调频信号，基于 XWVD 谱峰检测的瞬时频率估计得到的结果是无偏的. 而且当幅度变化为先递减后递增时，估计结果可以取得比常数幅度时估计结果更好的统计性能. 并对迭代次数与信噪比的关系进行了分析.

第五章提出采用高斯函数的分数阶傅立叶变换作为基函数的自适应时频扩展，并给出了相应的自适应时频分布. 分数阶傅立叶变换使基函数的时频分布旋转了α 角度，结合尺度，时移和频移，使基函数在匹配信号时具有更大的灵活性. 由于自适应时频分布能够较好地描述信号的时频局部化特征，没有窗效应，没有交叉项的干扰，所以自适应时频分布为估计信号的瞬时频率提供一种新的工具. 应用自适应时频分布的谱峰检测来估计信号瞬时频率，不仅有较好的抗噪声干扰的能力. 而且对多分量信号，只要组成信号的各个分量在时频平面分隔开来，就可以用时变滤波器分离各个分量，估计出各个分量的瞬时频率. 仿真结果表明：自适应时频分布不但可以准确地估计信号的瞬时频率，而且还有很好的抗噪声的能力. 因此，应用自适应时频分布估计信号的瞬时频率为瞬时频率估计提供了一种新的途径.

第六章设计了基于信号瞬时频率和 WVD 结合的时变滤波器. 在时变滤波器中，关于 WVD 的信号综合是非常重要的. 本文采用最小二乘法成功地实现了 WVD 的信号综合：即求解出一最优时间序列，使它的 WVD 和修正的 WVD 的误差在最小均方意义下为最小，以此作为时变滤波器的输出. 最后，应用对比实例说明：对于非平稳信号而言，时变滤波器优于基于 FFT 技术的传统滤波器.

最后，对本文的工作作了总结，并展望可进一步研究的内容.

关键词 瞬时频率估计，时频分布，WVD，AM-FM 信号，XWVD，自适应信号扩展，自适应时频分布，时变滤波器

Abstract

Instantaneous frequency of a signal is a quantitative descriptor of many physical phenomena, sometimes we can grasp the characters of a physical process if we know well its instantaneous frequency. Instantaneous frequency is often of significant practical importance in many technical applications such as radar, sonar, and mobile communication. Therefore the study of the estimation method and application of instantaneous frequency can promote national economy and national defense. The time-frequency distribution gives rise to time-varying spectrum of a signal on the planar time-frequency plan, so the analysis and estimation on instantaneous frequency using the time-frequency distribution will be helpful to understand profoundly the physical senses. In fact, the estimation on instantaneous frequency is one of the tasks of two-dimensional time-frequency distribution. In this dissertation, the estimation method and application with instantaneous frequency using time-frequency distribution is deeply studied.

In chapter one, the fundamental concept of instantaneous frequency is introduced. The worldwide developments in this area are reviewed. The purpose and significance of the works in this dissertation are related.

In chapter two, the fast computation of WVD is studied. A new method transferring the computation of WVD into real field from complex field taking account of the conjugate symmetry of the WVD

kernel function has been introduced, which not only removes the redundancies in the WVD computation, but also make the length of kernel function reduced to a half. The realization of fast cosine operation and fast sine operation considerably reduces the computation cost by making full use of the periodicity and symmetry of the trigonometric function. The computation cost of the new method is now only $(N/2)\log 2^{N} - N$ real multiplication and $(2N-2)\log 2^{N} - 2N + 2$ real addition instead of $2N\log 2^{2N} - 7N + 6$ real multiplication and $3N\log 2^{2N} - 3N + 2$ real addition. It is obvious that the new method remarkably reduces the computation cost of the WVD. Further more, the method can be implemented by using the "same address", that is, we can use the same memory location to input and output. Preceding shows that the new algorithm provided in the paper is much more advantageous than the existed.

Chapter three studies the method to estimate instantaneous frequency of AM-FM signals using the peak of WVD and its performances. Analysis results show that the estimation on amplitude time-varying and frequency linear modulating signals will be unbiased, only if WVD of time-varying amplitude reaches its maximum at frequency zero no matter in which time, and the invariance is concluded in detail. The study results expand using condition for estimating the instantaneous frequency by using the peak of WVD. The simulations using signals modulated Gaussian in amplitude and linearly in frequency show that for four kinds varying amplitude signal with no noise, the instantaneous frequency can be estimated accurately when the condition is met. Furthermore the statistical results of estimation of signal with amplitude descending before rising are better than those of the estimation of signal with constant amplitude. This study results are meaningful for signal process, especially for time-frequency analysis.

In chapter four, the reason that the statistical results of estimating the instantaneous frequency using the peak of XWVD are much better than using the peak of WVD is given from statistics point of view. Namely XWVD of the signal under analysis can be estimated from XWVD of signal contaminated by noise, the result is unbiased, and the invariance equals to the invariance of the noise. So using the peak of XWVD, the instantaneous frequency of signal with low SNR can be estimated accurately. But in the case of WVD can't be estimated from WVD of signal contaminated by noise, say nothing of estimating the instantaneous frequency of the signal. The simulations show that the statistical results of the estimation of signal with amplitude descending before rising are better than those of the estimation of signal with constant amplitude. The relationship between iteration number needed for convergence and signal-to-noise ratio is discussed.

In chapter five, a method of adaptive signal expansion based on fractional Fourier transform of Gaussian functions as the elementary functions and the related adaptive time-frequency distribution is proposed. Fractional Fourier transform rotates the time-frequency distribution of the elementary functions, which will make the match between signal and the elementary functions more flexible in combination with scaling, time-shift and frequency-shift. Because adaptive time-frequency distribution is of better time-frequency resolution, free of window effect and cross-term interference, It is a good tool for the instantaneous frequency estimation. Estimating the instantaneous frequency using the peak of the adaptive time-frequency distribution is good at anti-noise and flexible in processing multi-component signals. Every component can be separated by using the time-varying filter when every component of the signal is separate on the planar time-frequency plan, then the instantaneous frequency of every component is estimated respectively. The simulations support our conclusion, hence the peak of adaptive time-frequency distribution is a new method to estimate the instantaneous frequency.

In chapter six, the time-varying filter based on the instantaneous frequency and WVD is designed. The WVD synthesis is complicated for the time-varying filter. It is achieved in the least-square error, namely find a discrete-time sequence whose WVD best approximates, in a least-square error sense, the corrected WVD. The discrete-time sequence is the output of the time-varying filter. The compared experiments show that the time-varying filter is better than traditional filter based on FFT for non-stationary signal.

In conclusion section, a brief summary of all discussed topics is given. Further possible studied topics about the estimation method and application of the instantaneous frequency in the future are pointed out.

Key words instantaneous frequency estimation, time-frequency distribution, WVD, AM-FM signal, XWVD, adaptive signal expansion, adaptive time-frequency distribution, time-varying filter

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