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論文内容要旨

Chapter 1 Introduction

Periodically Time-Varying (PTV) digital filters possess many interesting characteristics, which are different from time-invariant and genersl time-varying difital filters. By means of these characteristics, many signal processing processes in commumication systems, speech and image processing systems can be implemented compactly and speedy. Frequency scramble, Time Division Multiplex-Frequency Division Multiplex (TDM-FDM) transmultiplexers, MOdulator／DEModulator (MODEM), and bandwidth compressor are some application examples of PTV digital filters. Also, PTV digital filters can be used to process cyclostationary signals and implement multiplierless IIR time invariant digital filters. Moreover, multirate digital signal processing and Quadrature Mirror Filter (QMF) banks are closely related to PTV digital filters. However, few studies have been given on the design of PTV digital filters with high precision and high efficiency.

In general, PTV digital filters are designed according to the procedure as shown in Fig. 1. First of all, a difference equation to approximately implement the given specifications is designed. It is called approximation. When a difference equation is implemented on hardware,

finite wordlength effects such as roundoff noise and coefficient quantization errors occur. State-space approach is a powerful tool to analyze and minimize roundoff noise and coefficient sensitivity. After approximation, the difference equation is therefore transformed into state-space description. Using state-spac e approach, optimal structures such as minimum roundoff noise realizations and minimum sensitivity realizations are designed. It is called synthesis.

This thesis provides a unified design (approximation and synthesis) of PTV digital filters with high precision and high efficiency.

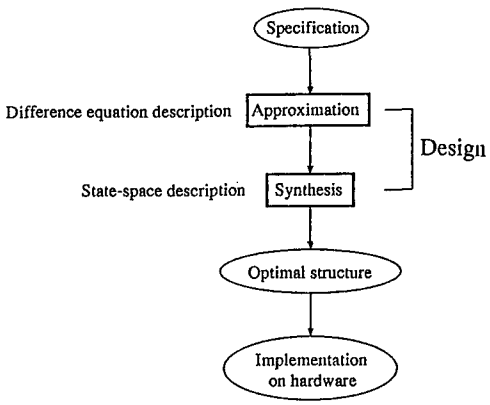

Figure 1 : Design procedure of PTV digital filters.

Chapter 2 Fundamental study of PTV digital filters

PTV digital filters are defined firstly. Then properties of PTV digital filters such as linearity, causality, stability, and cascade and parallel combinations of PTV digital filters are investigated. In particular, several special cases of cascade combination, which relate closely to the design of PTV digital filters, are considered.

"Equivalent models " is an important concept in the analysis and design of PTV digital filters. From the definition of PTV digital filters, we derive four equivalent modeld of PTV digital filters, i. e., Input Sampling Polyphase (ISP), Output Sampling Polyphase (OSP), transformed ISP, and transformed OSP models. Input-output characteristics of these four models in time and frequency domains are also investigated.

In addition, state-space and difference equation descriptions of PTV digital filters are discussed. Impulse responses and transfer functions are derived by using the PTV coefficients of state-space equations and difference equations respectively. It is shown that under some condition, defference equations can be trnasformed into state-space description. This is different from the time-invariant case.

Chapter 3 Approximation of PTV digital filters

In general, specifications of time-invariant digital filters of the equivalent model of a PTV digital filter are usually given as the specifications of the PTV digital filter. For this situation, we propose an efficient approximattion method. With this method, time-invariant digital filters of the equivalent model of a PTV digital filter are designed firstly to approximately

implement the given specifications. These filters are easily designed by using time-invariant approximation approach. Then a difference equation with PTV coefficients is designed by using extended Padé approximation to approximately implement the equivalent model. It is shown that the hardware and computation required to implement the difference equation compare favorably with existing approximation methods.

Chapter 4 Analysis of finite wordlength effects of PTV state-space digital filters

Equivalent block realizations of PTV state-space digital filters is introduced firstly. This is because the block realizations are Multi-Input and Multi-Output (MIMO) time-invariant state-space digital filters, and thus the analysis of finite wordlength effects of PTV state-space digital filters can be given with the help of time-invariant approaches.

Using the block realization of a PTV state-space digital filter, statistical analysis is discussed. In statistical analysis, we evaluate covariance of the state and variance of the output to a Gaussian input. Covariance matrices and covariance matrices of dual PTV state-space digital filters are derived.

Also, controllability and observability of PTV state-space digital filters are discussed. Necessary and sufficient conditions for controllability and observability are given. Controllability and observability Grammians are defined and derived, and are shown to be equal to the covariance matrices and the covariance matrices of dual PTV state-space digital filters. Using these Grammiams, we define balanced realizations which are important in the synthesis of minimum sensitivity realizations and model reduction.

Roundoff noise due to the quantization error of the multiplication results is defined and derived. It turns out that roundoff noise is expressed by so-called noise matrices which are the covariance matrices of dual PTV state-space digital filters.

Coefficient sensitivity is also investigated. Statistical sensitivity and frequency sensitivity are defined and derrived. It is shown that the expressions of statistical sensitivity and frequency sensitivity are the same although their definitions are extremely different.

Chapter 5 Synthesis of finite wordlength PTV state-space digital filters

Equivalent transformation is the foundation of the synthesis of state-space degital filters, and thus is introduced firstly.

Based on the statistical analysis results, l_2 scaling is considered.

Minimum roundoff noise realizations are synthesized under the l_2 scaling constraints. A synthesis procedure of minimum roundoff noise realizations is presented.

Synthesis of minimum sensitivity realizations is also discussed. It is shown that when *Period* $= 2$ balanced realizations have minimum sensitivity. Therefore synthesis of minimum

sensitivity realizations can be done by synthesizing balanced realizations. A synthesis procedure for balanced realizations is also presented.

Chapter 6 Applications of PTV digital filters

Implementation of TDM-FDM transmultiplexers by using PTV digital filters is proposed. Design examples of FIR and IIR PTV digital filters for 4 channel TDM-FDM transmultiplexers are given to verify the effectiveness of the proposed implementation. Comparison with three conventional methods shows that the proposed implementation greatly reduces the computation and hardware required.

In frequency scramble, original signals can not be reconstructed perfectly. This is because both frequency scramble and descramble make use of several bandpass filter, and these bandpass filters with ideal attenuation characteristics can not be designed and implemented in practical. In order to solve the problem, an encryption method using PTV digital filters is proposed. This method makes use of the principle of perfect reconstruction QMF banks. With the proposed encryption method, a digital signal can be encrypted without any expansion of bandwidth and reconstructed perfectly. A design example is given to verify the effectiveness of the encryption method. In particular, we make an experiment using speech signal and Digital Signal Processor (DSP) to investigate the encryption and decryption effects of the proposed encryption method and frequency scramble.

Chapter 7 Conclusions

Main analysis results of Chapters 2, 3, 4, 5, and 6 are summarized. Several unsolved problems are pointed out. Future research topics in the related fields are also introduced.

審 査 結 果 の 要 旨

周期的時変ディジタルフィルタは，時不変ディジタルフィルタでは実現することが困難な特性が容易に得られるので注目されている。しかし，高精度で低次数化されたフィルタの設計に関する研究は，従来ほとんど行われていなかった。

著者は周期的時変ディジタルフィルタを状態方程式で記述しその表現法を与え，それを用いることによりフィルタの設計を行う上で重要な基礎的性質を明らかにすると共に，高精度で低次数化されたフィルタの設計法を確立し，その有用性を実証した。本論文は，その成果をとりまとめたもので，全文7章よりなる。

第1章は緒言である。第2章では，周期的時変ディジタルフィルタの表現法を与え，その双対システムと等価変換を定義し，以下の章に役立つ基本的概念を提案している。

第3章では，周期的時変ディジタルフィルタの設計上基礎となる近似法について考察している。まず，与えられた周波数領域仕様，あるいは時間領域仕様を満足する等価モデルを導き，それに基づき拡張されたパデ近似法により差分方程式を低次数化する方法を明らかにしている。この方法は，必要とする次数が低く，かつ近似誤差が小さい周期的時変フィルタの実現を可能にする点で有用な成果である。

第4章では，周期的時変ディジタルフィルタのブロック実現を導入し，誤差最小のフィルタ構造を合成するために必要な係数感度と丸め誤差の解析を行っている。ブロック実現を用いることによって，周期的時変フィルタの量子化誤差の解析が，時不変フィルタの解析の問題に帰着されるため容易になることを見出している。

第5章では，前章で得られた解析結果に基づき，係数感度と丸め誤差が最小な周期的時変ディジタルフィルタの合成法を与えると共に，これにより得られる最適フィルタ構造と平衡形実現が等価であることを明らかにしている。これらは重要な成果である。

第6章では，周期的時変ディジタルフィルタの特長を生かした応用として，時分割多重／周波数分割多重変換器などの例を挙げ検討している。その結果，周期的時変フィルタの帯域分割と変調の二つの機能を活用することにより，従来法に比べて計算量やハードウェア量を少なくできることを示し，実験によりその有効性を確認している。

第7章は結言である。

以上要するに本論文は，従来ほとんど研究がなされていなかった、周期的時変ディジタルフィルタの近似法と合成法を明らかにし，高精度で低次数化されたフィルタの設計法を確立したもので，電子工学および情報工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。