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論　文　内　容　要　旨

1. Introduction

As hardware technology advances rapidly and integrated circuits become faster, cheaper and more compact year by year, digital signal processing has made many sophisticated problems solvable. It will play an increasingly important role in the multidimensional digital signal processsing and nonlinear, shift-variant digital signal processing.

Two-dimensional (2-D) digital filtering is one of the most important and fundamental processing techniques encountered in 2-D digital signal processing. To carry out 2-D digital filering, it is necessary to design 2-D digital filters (2DDF's) satisfying the processing requirements. However, since stability test for 2DDF's is extremely difficult and a latge amount of computations are needed in 2DDF design, the problem of designing 2DDF's is not easy to solve.

In this dissertation, the author proposed three techiques to decompose 2-D frequency domain design specifications into one-dimensinal (1-D) ones, and then the problem of designing 2DDF's is reduced to the problem of designing 1-D digital filters (1DDF's). Because the design techniques for designing 1DDF's have already been well developed and the stability test for 1DDF's is much easier than that for 2DDF's the original 2-D design problem can be significantly simplifed.

2. Two-Dimensinal Signals and Digiral Filters

In this chapter, the fundamental theory of 2-D digital filtering is summarized. In addition, the importance of reducing 2-D design problem to 1-D one is strongly emphasized.

3. Filter Design Based on the Decomposition of Complex Design Specifications

In this chapter, 2-D magnitude specification $M_d(\omega_1, \omega_2)$ and 2-D general phase specification $\phi_d(\omega_1, \omega_2)$ are assumed to be given as frequency domain specifications.

From 2-D magnitude specification $M_d(\omega_1, \omega_2)$ and phase specification $\phi_d(\omega_1, \omega_2)$, we can form the desired 2-D frequency response $H_d(\omega_1, \omega_2)$ as

$$H_d(\omega_1, \omega_2) = M_d(\omega_1, \omega_2) e^{j\phi_d(\omega_1, \omega_2)}. \tag{1}$$

Then by using the sampled the complex specification $H_d(\omega_1, \omega_2)$, we can construct a complex matrix

$$\boldsymbol{H} = \begin{bmatrix} \mathrm{H_d}(0,0) & \mathrm{H_d}(0,1) & \cdots & \mathrm{H_d}(0,\mathrm{N}) \\ \mathrm{H_d}(1,0) & \mathrm{H_d}(1,1) & \cdots & \mathrm{H_d}(1,\mathrm{N}) \\ \vdots & \vdots & & \vdots \\ H_d(M,0) & H_d(M,1) & \cdots & H_d(M,N) \end{bmatrix} \tag{2}$$

where $\boldsymbol{H} \in \boldsymbol{C}^{(M+1)\times(N+1)}$. Finally, the singular value decomposition (SVD) is applied to decompose the matrix $\boldsymbol{H}$

$$\boldsymbol{H} \approx \boldsymbol{H}_f \cdot \boldsymbol{H}_g \tag{3}$$

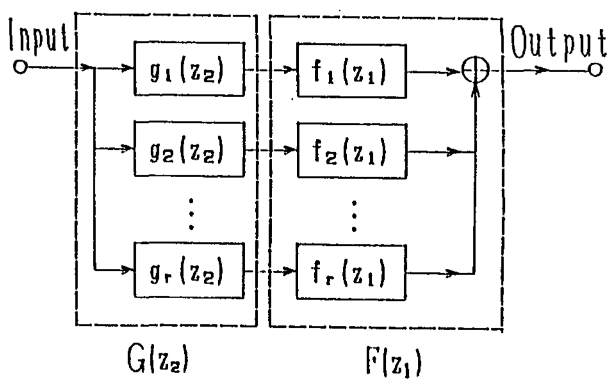

Figure 1 : 2DDF structure designed in Chapter 3.

where $H_f \in C^{(M+1)\times r}$, $H_g \in C^{r\times(M+1)}$. Consequently, matrix H_g and matrix H_f can be regarded as the 1-D frequency response specification matrice of a 1-input/r-output 1DDF $G(z_2)$ ***and*** r-input/1-output 1DDF $F(z_1)$ respectively. Therefore, to design a 2DDF $H(z_1, z_2)$, we only need to design a pair of 1DDF's, $F(z_1)$ and $G(z_2)$, and $H(z_1, z_2)$, can be synthesized as

$$H(z_1, z_2) = F(z_1)\, G(z_2) \tag{4}$$

In particular, if the matrix H is a Hermitian matrix, that is, $H = H^*$, to design a 2DDF $H(z_1, z_2)$, only one 1DDF ($F(z_1)$ or $G(z_2)$) needs to be designed. Thus the design problem becomes very easy to solve. Fig. 1 illustrates the structure of the designed 2DDF.

4. Filter Design Based on the Iterative Singilar Value Decomposition

In this chapter, 2-D magnitude specification $M_d(\omega_1, \omega_2)$ and 2-D group delay specifications $T_{1d}(\omega_1, \omega_2)$, $T_{2d}(\omega_1, \omega_2)$ are given as design speclfications, but the group delay specifications $T_{1d}(\omega_1, \omega_2)$ and $T_{2d}(\omega_1, \omega_2)$ are confined to be

$$\begin{aligned} T_{1d}(\omega_1, \omega_2) &= f_1(\omega_1) \\ T_{2d}(\omega_1, \omega_2) &= f_2(\omega_2) \end{aligned} \tag{5}$$

where $f_1(\omega_1)$ and $f_2(\omega_2)$ are real analytical functions of ω_1 and ω_2 respectively.

The main objective of this chapter is to propose a new technique for decomposing the 2-D magnitude specification matrix A, which is constructed by using the sampled $M_d(\omega_{1m}, \omega_{2n})$,

$$A = \begin{bmatrix} M_d(0,0) & M_d(0,1) & \cdots & M_d(0,N) \\ M_d(1,0) & M_d(1,1) & \cdots & M_d(1,N) \\ \vdots & \vdots & & \vdots \\ M_d(M,0) & M_d(M,1) & \cdots & M_d(M,N) \end{bmatrix} \tag{6}$$

into the form

$$A \approx \sum_{i=1}^{r} S_i F_i G_i \tag{7}$$

where $S_i = 1$ or $S_i = -1$, and all the elements of F_i, and G_i are nonnegative so that they can be reguarded as 1-D magnitude specifications directly.

In this chapter, the proposed new technique is called the ***Iterative Singular Value Decomposition (ISVD)***.

Based on the decomposition (7), matrices F and G

$$F = [F_1\ F_2 \cdots F_r] \qquad G = \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_r \end{bmatrix} \tag{8}$$

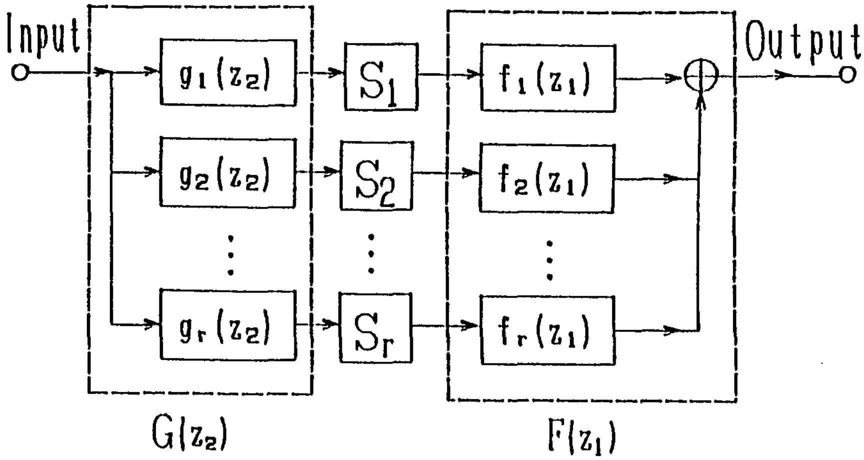

Figure 2 : 2DDF structure designed in Chapter 4 and Chapter 5.

can be obtained and reguarded as the magntude specification matrices of an r-input/1-output 1DDF $\boldsymbol{F}(z_1)$ and a 1-input/r-output 1DDF $\boldsymbol{G}(z_2)$ rerespectively. To design a 2DDF $H(z_1, z_2)$, only a pair of 1DDF's $\boldsymbol{F}(z_1)$ and $\boldsymbol{G}(z_2)$ need to be designed, and $H(z_1, z_2)$ can be synthesized as

$$H(z_1, z_2) = \boldsymbol{F}(z_1)\boldsymbol{S}\boldsymbol{G}(z_2) \tag{9}$$

where $\boldsymbol{S}$ is a diagonal matrix, $\boldsymbol{S} = diag(S_1, S_2, \cdots, S_r)$. The structure is graphically depicted as Fig. 2. The magnitude response and group delay responses in the passband of a designed 2DDF are shown in Fig. 3 and Fig. 4.

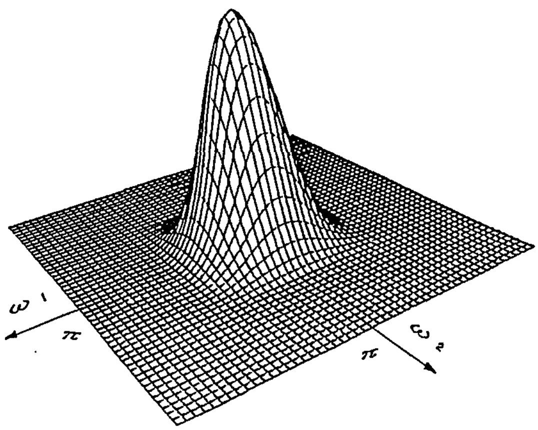

Figure 3 : 2-D magnitude response.

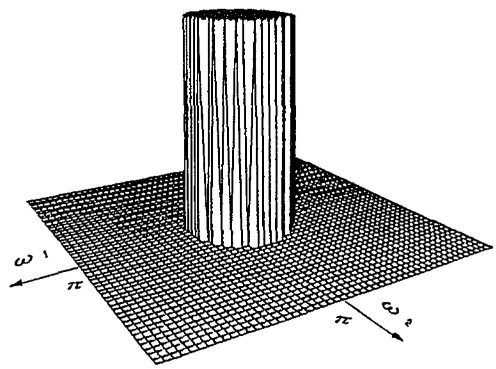

Figure 4 : 2-D group delay responses $t_1(\omega_1, \omega_2) = t_2(\omega_2, \omega_1)$.

5. Filter Design Based on the Optimal Decomposition

By using the ***ISVD***, 2-D magnitude specification matrix A can be decomposed into the form

$$A \approx \sum_{i=1}^{r} S_i F_i G_i \tag{10}$$

but the decomposition error E

$$E = \| A - \sum_{i=1}^{r} S_i F_i G_i \|_2 \tag{11}$$

is not minimum.In the case that the error E is not small enough, the ***Optimal Decomposition*** (***OD***) to be proposed below in this chapter should be utilized.

If the decomposition (10) satisfies the conditions

(a) all the elements of vectors F_i and G_i are nonnegative,

(b) $S_i = 1$ or $S_i = -1$, and the rms error E

$$E = \| A - \sum_{i=1}^{r} S_i F_i G_i \|_2 \Rightarrow \text{minimum}, \tag{12}$$

the decomposition (10) is defined as the ***Optimal Decomposition*** (***OD***). The strict constraints (a), (b) imposed on the OD make the decomposition problem be nonlinear. In this chapter, the following variable substitutions

$$F_i = [e^{x_{i0}}\ e^{x_{i1}}\ \cdots\ e^{x_{iM}}]^t \tag{13}$$

$$G_i = [e^{y_{i0}}\ e^{y_{i1}}\ \cdots\ e^{y_{iM}}] \tag{14}$$

are performed first,and then the erroe E is minimized by nonlinear optimization technique. In addition, the ISVD results are chosen as initial values, the optimal point can be easily reached. The 1DDF design procedures are the same as those in the preceding chapter.

6. Conclusions and Suggestions

The decomposition-based design techniques proposed in this dissertation possess the following advantages:

(1). the resulting 2DDF's are always stable,

(2). design accuracy is very high,

(3). the structures of the designed 2DDF's possess high parallelism, modularity and regularity,

(4). significant reduction in computational complexty can be achieved.

Based on the research in this dessetation, several further study subjects are also suggested.

審査結果の要旨

最近，画像処理などの２次元信号処理の必要性に伴い，２次元ディジタルフルタの設計に関する多くの研究がなされている。しかし，２次元ディジタルフィルタの設計においては，安定性を保証することが難しく，パラメータ数が多いことなどのために，高精度でパラメータ数が少ない設計に関する研究が望まれていた。著者は，２次元の周波数領域仕様の様々な分解の概念を提案し，これを用いて高精度かつ効率的な２次元ディジタルフィルタの設計法を与えた。本論文は，それらの成果をとりまとめたもので，全文６章よりなる。

第１章は緒言である。

第２章では，２次元ディジタル信号処理の基礎時効を整理し，２次元ディジタルフィルタとその仕様の分解の基礎概念を整理するとともに，これに基づくフィルタ設計上の課題を検討している。

第３章では，２次元の複素設計仕様の分解について考察するとともに，これに基づく２次元ディジタルフィルタの設計法を与えている。この方法は，１次元ディジタルフィルタの組み合わせによって２次元ディジタルフィルタを近似しているが，近似誤差の少ない２次元ディジタルフィルタを設計できる点で優れている。

第４章では，まず特異値分解を主とする従来の分解法が，設計仕様として与えられた２次元の非負の振幅特性を負の部分を有する振幅特性に分解するため，フィルタの設計には適さないことを指摘している。この考察に基づき，非負の結果を与える分解法として逐次特異分解を提案し，そのアルゴリズムを与えている。次に，逐次特異値分解に基づき２次元ディジタルフィルタの設計を行い，設計仕様の対称性を利用することによって設計に要するパラメータ数が従来の設計法に比べて約半減することを確認している。

第５章では，逐次特異値分解の概念を発展させて，最適分解を提案しそのアルゴリズムを与えている。最適分解は，２次元の振幅仕様の非負の分解結果を与え，かつその分解の誤差が最小である。最適分解に基づく２次元ディジタルフィルタの設計法は，その分解の最適性ならびに設計仕様の対称性を利用することにより，従来の設計法に比べ設計に要するパラメータ数が半分以下となり，さらに近似精度が極めて高いことを数多くの設計例から明らかにしている。これは重要な成果である。

第６章は結言である。

以上要するに本論文は，２次元ディジタルフィルタの設計に適した新しい周波数領域仕様の分解法を与えるとともに，これに基づいた２次元ディジタルフィルタの最適設計法を確立したものであり，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，本論文は工学博士の学位論文として合格と認める。