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POLYNOMIAL FACTORIZATION USING RECURSIVE FORMULAS
FOR COMPLEX INTEGRALS

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JUNE 1981

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Abstract The complex integrals $I(\lambda) = \frac{1}{2\pi i} \int \frac{\varrho A(z)A(z^{-1}) + B(z)B(z^{-1})}{C(z)C(z^{-1})} \frac{dz}{z^{\lambda+1}}$ can be used to solve the spectral factorization problem $P(z)P(z^{-1}) = \varrho A(z)A(z^{-1}) + B(z)B(z^{-1})$ which appears in LQG calculations. This method has high precision. The report gives recursive formulas for evaluating $I(\lambda)$ and two iterative algorithms for the spectral factorization. Two test programs are written in PASCAL. The calculation of $I(0)$ also gives a test for the stability of the polynomial $P(z)$ in each iteration.			
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1. INTRODUCTION

Consider a discrete time system governed by the model

$$A(z) y(t) = B(z) u(t) \quad (1.1)$$

Let the criterion be to minimize

$$J = \sum_{t=0}^{\infty} [y^2(t) + \rho u^2(t)] \quad (1.2)$$

The solution of this optimization problem gives a closed loop system whose characteristic polynomial $P(z)$ is given by

$$P(z)P(z^{-1}) = \rho A(z)A(z^{-1}) + B(z)B(z^{-1}) \quad (1.3)$$

where P , A and B are polynomials with real coefficients.

$$P(z) = p_0 z^k + p_1 z^{k-1} + \dots + p_k$$

$$A(z) = a_0 z^k + a_1 z^{k-1} + \dots + a_k$$

$$B(z) = b_0 z^k + b_1 z^{k-1} + \dots + b_k$$

and ρ is a weighting factor. See Astrom (1979). For self-tuning regulators it is useful to have efficient algorithms to solve the design problem.

It can be shown that the right hand side of (1.3) can be factorized when $\rho \geq 0$. Consider a stationary discrete stochastic process

$$y(t) = r A(z) w(t) + B(z) v(t) \quad (1.4)$$

where $w(t)$ and $v(t)$ are uncorrelated white noises and the coefficients a_i and b_i are real numbers. Consider also another stationary discrete time process with white noise input $\varepsilon(t)$

$$z(t) = P(z) \varepsilon(t) \quad (1.5)$$

where $P(z)$ is a real coefficient polynomial. These two processes are equivalent in the sense of that they have same spectral density function, i.e.

$$\phi_y(\omega) = \phi_z(\omega)$$

Let $\varrho = r^2$, then (1.3) follows. (1.3) has several solutions because of

$$\begin{aligned} P(z)P(z)^{-1} &= k_1 \prod_{i=1}^k (z - r_i)(z^{-1} - r_i^{-1}) \\ &= k_2 \prod_{i=1}^k (z - 1/r_i)(z^{-1} - 1/r_i) \end{aligned} \quad (1.6)$$

where k_1 and k_2 are constants. The resultant polynomial $P(z)$ is the combination of all possible zeros, but there is only one combination with

$$|z_i| \leq 1 \quad \text{for } i=0,1,\dots,k$$

which corresponds to a stable polynomial $P(z)$.

The complex integral

$$I(k) = \frac{1}{2\pi i} \oint \frac{\varrho A(z)A(z)^{-1} + B(z)B(z)^{-1}}{C(z)C(z)^{-1}} dz \quad (1.7)$$

is related to the factorization problem. The efficient algorithm Astrom et al (1970) and Astrom (1970) for evaluating $I(0)$ can be used to solve (1.7), and the calculation of $I(0)$ can also give a test for the stability of the polynomial $P(z)$, which is described in previous literatures.

This report is organized as follows. The iteration method and the relationship between $I(k)$ and coefficients of $P(z)$ is described in section 2. The recursive formulas are given in section 3. A numerical example shows that the method based on the complex integral has high precision. Section 4 shows a reduced version of recursive formulae which requires less computing times than the former. Two programs in PASCAL are given in appendices.

2. ITERATION METHOD AND RELATIONSHIPS

A method based on Newton iteration is suggested by Kucera et al (1976) and Kucera (1979) because it features monotone and essentially quadratic convergence. Define polynomials $C(z)$ and $X(z)$ with

$$\deg C_J(z) = \deg X_J(z) = \deg P_J(z)$$

where subscript J denotes the J th iteration. The iteration is performed recursively by solving

$$C_J(z)X_J(z)^{-1} + X_J(z)C_J(z)^{-1} = \varrho A(z)A(z)^{-1} + B(z)B(z)^{-1} \quad (2.1)$$

starting from a stable polynomial $C_0(z)$. The next polynomial in the iteration is then given by

$$C_{J+1}(z) = -\frac{1}{2} [C_J(z) + X_J(z)] \quad (2.2)$$

and the desired polynomial $P(z)$ is obtained as

$$P(z) = \lim_{J \rightarrow \infty} C_J(z) \quad (2.3)$$

In practice it only takes a few steps for $C(z)$ to converge to the desired polynomial. The test

$$|c_{i,j+1} - c_{i,j}| < \text{eps} \quad \text{for } i=0,1,\dots,n$$

where eps is a given small value, can be used to stop the recursion.

Equation (2.1) can be written as a set of linear equations

$$CX = 2(\varrho a + b) \quad (2.4)$$

where C is a square matrix of dimension k given by

$$C = \begin{bmatrix} 2c_0 & 2c_1 & 2c_2 & \dots & 2c_{k-2} & 2c_{k-1} & 2c_k \\ c_1 & c_0 & c_2 & c_1 & c_3 & \dots & c_{k-3} & c_{k-2} & c_{k-1} & c_k \\ c_2 & c_3 & c_0 & c_4 & \dots & c_{k-4} & c_k & c_{k-1} & c_{k-2} & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ c_{k-1} & c_k & 0 & \dots & 0 & \dots & 0 & c_0 & c_1 & \dots \\ c_k & 0 & 0 & \dots & 0 & \dots & 0 & 0 & c_0 & c_1 \end{bmatrix}$$

and a and b are vectors of the same form

$$a = \begin{bmatrix} \sum_{i=0}^k a_i \\ \sum_{i=0}^{k-1} a_{i+1} \\ \sum_{i=0}^{k-2} a_{i+2} \\ \dots \\ \sum_{i=0}^1 a_{i+k-1} \\ a_k \end{bmatrix}$$

If $C(z)$ is a stable polynomial, dividing both sides of (2.1) by $C(z)C(z)^{-1}$ gives

$$\frac{C(z)X(z)^{-1} + X(z)C(z)^{-1}}{C(z)C(z)^{-1}} = \frac{2[\varrho A(z)A(z)^{-1} + B(z)B(z)^{-1}]}{C(z)C(z)^{-1}} \\ = 2 \sum_{l=-\infty}^{\infty} I(l) z^l \quad (2.5)$$

$$\text{or } \frac{X(z)}{C(z)} = I(0) + 2 \sum_{l=-\infty}^{-1} I(l) z^l \quad (2.6)$$

Applying long division to the left side of (2.6) we have

$$\frac{X(z)}{C(z)} = \frac{x_0}{c_0} + \frac{1}{c_0} \left(x_1 - \frac{c_1}{c_0} x_0 \right) z^{-1} + \dots \quad (2.7)$$

Equating coefficients of same powers of (2.6) and (2.7) gives

$$I(0) = x_0 / c_0$$

$$I(1) = (x_1 - x_0 c_1 / c_0) / 2c_0$$

...

$$I(l) = [x_l - x_0 c_l / c_0 - (x_1 - x_0 c_1 / c_0) c_l / c_0 - \dots - 1/2 c_0$$

...

$$\text{or } X = C_1 I \quad (2.8)$$

where

$$C_1 = \begin{bmatrix} c_0 & 0 \\ c_1 & 2c_0 \\ c_k & 2c_{k-1} \dots 2c_0 \end{bmatrix}$$

EXAMPLE 1.

Given the polynomials

$$P(z) = p_0 z + p_1 \quad \text{and}$$

$$C(z) = c_0 z + c_1$$

Solve

$$\begin{bmatrix} 2c_0 & 2c_1 \\ c_1 & c_0 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \end{bmatrix} = \begin{bmatrix} 2(p_0^2 + p_1^2) \\ 2 p_0 p_1 \end{bmatrix}$$

We find

$$x_0 = [(p_0^2 + p_1^2)c_0 - 2p_0 p_1 c_1] / (c_0^2 - c_1^2)$$

$$x_1 = [2p_0 p_1 c_0 - (p_0^2 + p_1^2)c_1] / (c_0^2 - c_1^2)$$

Substituting x_0 and x_1 into (2.7), we obtain

$$\begin{aligned} 2I(1) &= (c_0 x_1 - c_1 x_0) / c_0^2 \\ &= [2p_0 p_1 (c_0^2 + c_1^2) - 2(p_0^2 + p_1^2)c_0 c_1] / [c_0^2 (c_0^2 - c_1^2)] \end{aligned}$$

Integral $I(1)$ can be also obtained by use of residue theorem

Let

$$\phi(z) = \frac{P(z)P(z^{-1})}{C(z)C(z^{-1})} z^{-2}$$

Then

$$\begin{aligned}
I(1) &= \sum_i |z|^{1-i} \operatorname{Res} \{ \phi(z) \} z \rightarrow z_i \\
&= \lim_{z \rightarrow 0} [z^2 \phi(z)]' + \lim_{z \rightarrow -c/c_1} [(z - c/c_1) \phi(z)] \\
&= [p_0 p_1 (c_1^2 + c^2) - (p_0^2 + p_1^2) c c_1] / [c_0^2 (c_1^2 - c^2)] \\
&\quad \square
\end{aligned}$$

Substituting (2.8) into (2.5) gives a set of linear equations for $I(1)$

$$C C_1 I = \varrho a + b \quad (2.9)$$

Notice that the matrix $C C_1$ will be symmetric if its first row is divided by 2.

EXAMPLE 2.

Consider a second order system in the form of (2.9)

$$\begin{bmatrix} (c+c_1^2)/2 & c c_1 + c c_1^2 & c c_1^2 \\ c c_1 + c c_1^2 & c_1^2 + c + c c_1^2 & c c_1 \\ c c_1^2 & c c_1 & c_1^2 \end{bmatrix} \begin{bmatrix} I(0) \\ I(1) \\ I(2) \end{bmatrix} = \begin{bmatrix} (p_0^2 + p_1^2)/2 \\ p_0 p_1 + p_1^2 \\ p_0 p_2 \end{bmatrix}$$

A simple nonsingular transformation T_1^T brings $C C_1$ to an upper triangular matrix

$$C C_1^T T_1 = \begin{bmatrix} (c+c_1^2)/2 & c c_1 + c c_1^2 & c c_1^2 \\ 0 & c_1^2 + c + c c_1^2 & c c_1 \\ 0 & 0 & c_1^2 \end{bmatrix}$$

where

$$T_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -c/c_1 & -c_1/c & 1 \end{bmatrix}$$

and

$$T_2 = \begin{bmatrix} 1 & 0 & 0 \\ -c_1/(c_1+c_2) & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Then $I(0)$, $I(1)$ and $I(2)$ can be obtained by back substitution.

□

An alternative approach is to reduce the calculation of $I(1)$ to a problem which involves calculation of square loss function. Recursive equations are given in the next section.

3. RECURSIVE FORMULAS FOR $I_k(z)$

An efficient tool developed by Astrom (1970) for evaluating loss function can be exploited to solve (1.7). Introduce

$$C_k^*(z) = z C_k(z^{-1}) = c_0^k + c_1^k z + \dots + c_k^k z^k$$

$$B_k^*(z) = z B_k(z^{-1}) = b_0^k + b_1^k z + \dots + b_k^k z^k$$

and

$$Q_k(l, z) C_k(z) + R_k(l, z) = z^l B_k(z) \quad (3.1)$$

where $Q_k(l, z)$ and $R_k(l, z)$ are the quotient and the remainder

of the polynomial division (3.1). In this section we only give the formulas for the second term of the right hand side of (2.3) because formulas for the first term have the same form.

Consider the complex integral

$$\begin{aligned} I_k(l) &= \frac{1}{2\pi i} \oint \frac{z^l B_k(z) B_k^*(z^{-1})}{C_k(z) C_k^*(z^{-1})} \frac{dz}{z} \\ &= \frac{1}{2\pi i} \oint \left[\frac{Q_k(l, z) B_k^*(z)}{C_k^*(z)} + \frac{R_k(l, z) B_k^*(z^{-1})}{C_k(z) C_k^*(z^{-1})} \right] \frac{dz}{z} \\ &= Q_k(l, 0) \frac{b_0^k}{c_0^k} + \frac{1}{2\pi i} \oint \frac{R_k(l, z) B_k^*(z^{-1})}{C_k(z) C_k^*(z^{-1})} \frac{dz}{z} \quad (3.2) \end{aligned}$$

Equation (3.1) is then reduced to a simple complex integral. In similar way define

$$C_{k-1}^*(z) = z^{-1} [C_k(z) - \alpha_k^* C_k^*(z)]$$

$$\alpha_k = c_k^k / c_0^k$$

$$B_{k-1}^*(z) = z^{-1} [B_k(z) - \beta_k^* C_k^*(z)]$$

$$\beta_k = b_k^k / c_0^k$$

$$\text{and } R_{k-1}(l, z) = z^{-1} [R_k(l, z) - \gamma_k^* C_k^*(z)]$$

$$\gamma_k = r_k^k / c_0^k$$

Recursive formulas for the complex integral

$$\begin{aligned} I_{k-1}^0(\lambda) &= \frac{1}{2\pi i} \oint \frac{R_{k-1}(\lambda, z) B_{k-1}^{-1}(z^{-1})}{C_{k-1}(z) C_{k-1}^{-1}(z^{-1})} \frac{dz}{z} \\ &= \left[\frac{1}{2\pi i} \oint \frac{R_{k-1}(\lambda, z) B_{k-1}^{-1}(z^{-1})}{C_k(z) C_k^{-1}(z^{-1})} \frac{dz}{z} - \frac{1}{1 - \alpha_k} \frac{1}{z} \right] \end{aligned}$$

Substituting $R_{k-1}(\lambda, z)$ and $B_{k-1}^{-1}(z^{-1})$ into the above equality we get

$$\begin{aligned} (1 - \alpha_k) I_{k-1}^0(\lambda) &= \frac{1}{2\pi i} \oint \frac{[R_k(\lambda, z) - \gamma_k^* C_k^*(z)] [B_k(z^{-1}) - \beta_k^* C_k^*(z^{-1})]}{C_k(z) C_k^{-1}(z^{-1})} \frac{dz}{z} \\ &= I_k^0(\lambda) - \frac{\beta_k}{2\pi i} \oint \frac{R_k(\lambda, z)}{C_k^*(z)} \frac{dz}{z} - \frac{\gamma_k}{2\pi i} \oint \frac{B_k(z^{-1})}{C_k(z^{-1})} \frac{dz}{z} + \beta_k \gamma_k \\ &= I_k^0(\lambda) - \beta_k \gamma_k \end{aligned}$$

Hence

$$\begin{aligned} I_k^0(\lambda) &= (1 - \alpha_k^2) I_{k-1}^0(\lambda) + \beta_k \gamma_k \\ &= \frac{1}{c_0} \sum_{i=0}^k \frac{b_i^i r_i^i}{c_0} \frac{i}{c_0} \end{aligned} \quad (3.3)$$

and

$$I_k(\lambda) = Q_k(\lambda, 0) \frac{b_0^k}{c_0} + \frac{1}{c_0} \sum_{i=0}^k \frac{b_i^i r_i^i}{c_0} \frac{i}{c_0} \quad (3.4)$$

Equation (3.4) is a useful recursive formula for computing $I(\lambda)$. The polynomials $Q(\lambda, z)$ and $R(\lambda, z)$ can be obtained in a straightforward manner from (3.1)

$$\left. \begin{aligned} Q_k(l, z) &= q_0^l z^l + q_1^l z^{l-1} + \dots + q_l^l \\ R_k(l, z) &= r_1^k z^k + r_2^k z^{k-1} + \dots + r_k^k \end{aligned} \right\} \quad (3.5)$$

where

$$\left. \begin{aligned} q_0 &= b_0 / c_0 \\ q_1 &= (b_1 - q_0 c_1) / c_0 \\ &\dots \\ q_l &= (b_l - q_0 c_l - q_1 c_{l-1} - \dots - q_{l-1} c_1) / c_0 \\ r_1 &= b_{l+1} - q_0 c_{l+1} - q_1 c_l - \dots - q_l c_1 \\ r_2 &= b_{l+2} - q_0 c_{l+2} - q_1 c_{l+1} - \dots - q_l c_2 \\ &\dots \\ r_k &= -q_0 c_{l+k} - q_1 c_{l+k-1} - \dots - q_l c_k \end{aligned} \right\} \quad (3.6)$$

The coefficients of $Q(l, z)$ and $R(l, z)$ can also be obtained by using the following table

$$\begin{array}{ccccccc} & b_0 & b_1 & b_2 & \dots & b_k & \\ q_0 = b_0/c_0 & c_0 & c_1 & c_2 & \dots & c_k & \\ q_1 = r_1(0)/c_0 & c_0 & c_1 & \dots & c_{k-1} & c_k & \\ & r_1(0) & r_2(0) & \dots & r_k(0) & & \\ q_2 = r_1(1)/c_0 & c_0 & c_1 & \dots & c_{k-2} & c_{k-1} & c_k \\ & r_1(1) & r_2(1) & \dots & r_{k-1}(1) & r_k(1) & \\ & c_0 & c_1 & \dots & c_{k-1} & c_k & \\ & r_1(k-1) & r_2(k-1) & \dots & r_{k-1}(k-1) & r_k(k-1) & \\ q_k = r_1(k-1)/c_0 & c_0 & c_1 & \dots & c_{k-1} & c_k & \\ & r_1(k) & r_2(k) & \dots & r_{k-1}(k) & r_k(k) & \end{array}$$

Table 1. Long division of polynomials.

EXAMPLE 3.

We will consider the same problem as in Example 1. The integral $I(1)$ will be determined using (3.4).

- 1) Use Table 1 to determine $Q(1,z)$ and $R(1,z)$

$$q = \begin{matrix} p_0 & p_1 \\ 0 & 0 \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} p_0 & p_1 \\ c_0 & c_1 \end{matrix}$$

$$q_1 = \begin{matrix} (p_1 - p_0 c/c)/c \\ 0 \\ 0 \end{matrix}$$

$$\begin{matrix} p_1 - p_0 c/c \\ c_0 \end{matrix}$$

$$c_1$$

$$-(p_1 - p_0 c/c)c/c$$

$$\text{Hence } Q_1(1,z) = p_0/c \cdot z + (p_1 - p_0 c/c)/c$$

$$R_1(1,z) = -(p_1 - p_0 c/c)c/c$$

- 2) Use another table similar to Astrom(1970), called

table 2 ,to determine c_i^i , r_i^i and p_i^i .

$$\begin{array}{c|c|c} \begin{matrix} c_0 \\ c_1 \end{matrix} & \begin{matrix} p_0 \\ c_1 \end{matrix} & \begin{matrix} p_1 \\ c_0 \end{matrix} \\ \hline \begin{matrix} c_0^{-c}c/c \\ 0 \\ 1 \\ 0 \end{matrix} & \begin{matrix} p_0^{-p}c/c \\ 0 \\ 1 \\ 0 \end{matrix} & \begin{matrix} (p_1 - p_0 c/c)c/c \\ 0 \\ 1 \\ 0 \end{matrix} \end{array}$$

$$\begin{matrix} 0 \\ c_1 \end{matrix} \quad \begin{matrix} p_1 \\ c_0 \end{matrix} \quad \begin{matrix} -(p_1 - p_0 c/c)c/c \\ 0 \\ 1 \\ 0 \end{matrix}$$

The last row gives c_0^0 , p_0^0 and r_0^0 .

- 3) Equation (3.4) now gives

$$\begin{aligned} I_1(1) &= q_1 \frac{p_0}{c_0} + \frac{1}{c_0} \left[\frac{p_1}{c_0} + \frac{p_0^r}{c_0} \right] \\ &= [p_0 p_1 (c_0^2 + c_1^2) - (p_0^2 + p_1^2) c_0 c_1] / [c_0^2 (c_0^2 + c_1^2)] \quad \square \end{aligned}$$

Summary

Summing up, we get the following algorithm for solving the factorization problem (1.3).

- 1) Given $A(z)$, $B(z)$ and ϱ .
- 2) Solve the Newton iteration equation (2.1) with the initial polynomial

$$C_0(z) = 1$$

It follows from (2.5) that

$$C X_1 = 2 \varrho a$$

$$C X_2 = 2 b$$

and

$$X = X_1 + X_2$$

It follows from (2.1) that it is sufficient to find x_i for $i=0$ to $k-2$ if the order of $A(z)$ is k . The variable x_k can be obtained from the $(k+1)$ th row. and x_{k-1} is then obtained by substitution.

3) X is given by $I(1)$, see (2.8) where $I(1)$ is given by recursive formulae (3.4). It is convenient to use Table 1 and Table 2 to solve this problem.

EXAMPLE 4.

Given $\varrho = 3$ and

$$A(z) = z^3 + 3z^2 + 3z + 3$$

$$B(z) = z^3 + 3z^2 + 3z + 3$$

Factorize $P(z)$ by means of the program called REFAC1 listed in appendix A.

step	c_0	c_1	c_2	c_3
0	1.000000	0.000000	0.000000	0.000000
1	56.500000	84.000010	48.000000	12.000000
2	29.191400	42.015720	24.027940	6.012446
3	16.140390	21.132080	12.227490	3.099148
4	10.049080	11.136740	7.002997	1.913081
5	7.291217	7.128360	5.556308	1.719164
6	6.305313	6.154831	5.727749	1.878278
7	6.041695	6.018396	5.958360	1.981686
8	6.001110	6.000490	5.998890	1.999510
9	6.000001	6.000000	6.000000	2.000000
10	6.000000	6.000000	6.000000	2.000000
11	6.000000	6.000000	6.000000	2.000000
12	6.000000	6.000000	6.000000	2.000000

The resultant polynomial $P(z)$ is given by

$$P(z) = 6z^3 + 6z^3 + 6z + 2$$

The number of steps required for convergence depends on the initial condition. Convergence is faster if $C_0(z)$ is closer to $P(z)$ as is seen in the following table.

step	C_0	C_1	C_2	C_3
0	10.583000	7.937253	4.535573	1.133893
1	7.416798	6.534993	4.937915	1.473130
2	6.382465	6.171319	5.626061	1.823389
3	6.063704	6.028771	5.936308	1.971217
4	6.002530	6.001125	5.997470	1.998875
5	6.000004	6.000002	5.999996	1.999998
6	6.000000	6.000000	6.000000	2.000000
7	6.000000	6.000000	6.000000	2.000000
8	6.000000	6.000000	6.000000	2.000000
9	6.000000	6.000000	6.000000	2.000000
10	6.000000	6.000000	6.000000	2.000000
11	6.000000	6.000000	6.000000	2.000000
12	6.000000	6.000000	6.000000	2.000000

This example is not a real system, but it shows that the method has a high precision. Another result obtained by a method of elimination is given for comparison.

step	C_0	C_1	C_2	C_3
0	10.583000	7.937253	4.535573	1.133893
1	7.416800	6.534993	4.937914	1.473130
2	6.382465	6.171319	5.626060	1.823389
3	6.063703	6.028772	5.936308	1.971218
4	6.002529	6.001125	5.997470	1.998876
5	6.000006	6.000002	5.999996	1.999997
6	6.000000	6.000000	6.000000	2.000000
7	6.000002	6.000000	6.000000	1.999999
8	6.000000	5.999999	6.000001	2.000000
9	6.000001	6.000001	5.999999	2.000000
10	6.000000	6.000000	6.000001	2.000000
11	6.000001	6.000000	6.000000	2.000000
12	6.000002	6.000000	5.999999	1.999999

4. REDUCED_VERSION

The disadvantage of the algorithm given in section 3 is that it requires computation time more than some other methods. This problem can be solved by a modified algorithm. Consider

$$\begin{aligned} \rho A(z)A(z)^{-1} + B(z)B(z)^{-1} &= s_0 + s_1(z+z^{-1}) + \dots + s_k(z+z^{-k}) \\ &= (s_k z^{2k} + s_{k-1} z^{2k-1} + \dots + s_0 z^k + \dots + s_k) z^{-k} \\ &= S(z) z^{-k} \end{aligned} \quad (4.1)$$

The integral (1.7) becomes

$$\begin{aligned} I(\lambda) &= \frac{1}{2\pi i} \oint \frac{\rho A(z)A(z)^{-1} + B(z)B(z)^{-1}}{C(z)C(z)^{-1}} \frac{dz}{z^{\lambda+1}} \\ &= \frac{1}{2\pi i} \oint \frac{S(z)z^{-k}}{C(z)C(z)^{-1}} \frac{dz}{z^{\lambda+1}} \\ &= \frac{1}{2\pi i} \oint \left[\frac{S_q(z)z^{-k}}{C(z)^{-1}} + \frac{S_r(z)z^{-k}}{C(z)C(z)^{-1}} \right] \frac{dz}{z^{\lambda+1}} \\ &= \frac{1}{2\pi i} \oint \frac{S_r(z)z^{-k}}{C(z)C(z)^{-1}} \frac{dz}{z^{\lambda+1}} \end{aligned} \quad (4.2)$$

where

$$S_q(z)C(z) + S_r(z) = S(z) \quad (4.3)$$

$$S_q(z) = s_{q0}z^k + s_{q1}z^{k-1} + \dots + s_{qk-1}z$$

$$S_r(z) = s_{r0}z^k + s_{r1}z^{k-1} + \dots + s_{rk-1}z + s_{rk}$$

or in matrix form

$$\begin{bmatrix} c_0 & & & & & \\ c_1 & c_0 & & & & \\ & \ddots & \ddots & \ddots & \ddots & \\ c_k & c_{k-1} & \dots & c_1 & & \\ 0 & c_k & \dots & c_2 & 0 & 1 \\ & \ddots & \ddots & \ddots & \ddots & \\ & & 0 & 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} s_{q0} \\ s_{q1} \\ \vdots \\ s_{r0} \\ s_{r1} \\ \vdots \\ s_{rk} \end{bmatrix} = \begin{bmatrix} s_0 \\ s_1 \\ \vdots \\ s_k \\ s_{k-1} \\ \vdots \\ s_0 \end{bmatrix}$$

The procedure now follows the previous one. Define

$$Q_s(\lambda, z)C(z) + R_s(\lambda, z) = z^{\lambda} S_r(z) \quad (4.4)$$

Replacing $R(\lambda, z)$ and $B(z)$ by $R_s(\lambda, z)$ and z^k in (3.2) gives

$$I_k(\lambda) = [Q_s(\lambda, 0) + r_0^0 / c_0^0] / c_0^k \quad (4.5)$$

There is a general formula for r_0^0 . Assume

$$R_k(\lambda, z) = r_1^{k-1} z^{k-1} + r_2^{k-2} z^{k-2} + \dots + r_k^0$$

It follows from the reduction rule that

$$R_{k-1}(\lambda, z) = z^{-1} [R_k(\lambda, z) - y_k^* C_k^*(z)] \quad y_k^k = r_k^k(\lambda) / c_0^k$$

Furthermore

$$r_0^0(\lambda) = k_1 r_1(\lambda) + k_2 r_2(\lambda) + \dots + k_k r_k(\lambda)$$

where

$$k_1 = -c_1^1 / c_0^1$$

$$k_2 = -[c_2^2 + c_1^2 k] / c_0^2$$

...

$$k_k = -[c_k^k + c_{k-1}^k k_1 + c_{k-2}^k k_2 + \dots + c_1^k k_{k-1}] / c_0^k$$

These equations can be written as

$$r_0^0(\lambda) = \sum_{i=1}^k k_i r_i(\lambda) \quad (4.6)$$

$$k = - \left(\sum_{j=1}^i c_j^i k_{i-j} \right) / c_0^i \quad \text{for } i=1 \text{ to } k \quad (4.7)$$

with $k_0 = 1$.

EXAMPLE 5.

Consider the same problem as in Example 1. We have

$$S(z) = p_0 z^2 + (p_1^2 + p_0^2)z + p_0 p_1 = s_0 z^2 + s_1 z + s_0$$

Determine $I(0)$ and $I(1)$ by use of the recursive formulas (4.5)

1) Use a table to determine $Q_s(0,z)$, $Q_s(1,z)$, $R_s(0,z)$ and $R_s(1,z)$.

$$q_0 = \begin{matrix} s_0 & s_1 & s_0 \\ 0 & c_0 & c_1 \\ 0 & 0 & 0 \end{matrix}$$

$$q_1 = \begin{matrix} s_0 & s_1 & s_0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{matrix} \quad \begin{matrix} s_1 & s_0 \\ c_1 & c_0 \\ 0 & 0 \end{matrix}$$

$$q_2 = \begin{matrix} s_0 & s_1 & s_0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{matrix} \quad \begin{matrix} s_1 & s_0 \\ c_1 & c_0 \\ 0 & 0 \end{matrix} \quad \begin{matrix} s_1 & s_0 \\ c_1 & c_0 \\ 0 & 0 \end{matrix}$$

$$q_2 = \begin{matrix} s_0 & s_1 & s_0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{matrix} \quad \begin{matrix} s_1 & s_0 \\ c_1 & c_0 \\ 0 & 0 \end{matrix} \quad \begin{matrix} s_1 & s_0 \\ c_1 & c_0 \\ 0 & 0 \end{matrix}$$

$$Q_s(0,z) = q_0 z + q_1$$

$$Q_s(1,z) = q_0 z^2 + q_1 z + q_2$$

$$R_s(0,z) = s_0 - q_1 c_1 = r_1(0)$$

$$R_s(1,z) = -q_2 c_1 = r_1(1)$$

2) Use table 2 to determine c_i^i

$$\begin{matrix} c_0 & c_1 \\ c_1 & c_0 \end{matrix}$$

$$c_0^{-c_1} c_1 / c_0$$

3) From (4.5), we obtain

$$\begin{aligned}
I(0) &= \{ q_1 + [r_1(0)c/c] / [c - c_1c/c] \} / c_0 \\
&= [(p_0^2 + p_1^2)c - 2p_0p_1c] / [c(c_0^2 - c_1^2)] \\
I(1) &= \{ q_2 + [r_1(1)c/c] / [c - c_1c/c] \} / c_0 \\
&= [p_0p_1(c_0^2 + c_1^2) - (p_0^2 + p_1^2)c_1] / [c_0^2(c_0^2 - c_1^2)]
\end{aligned}$$

□

The Simplified Algorithm

A reduced algorithm is now obtained as follows

- 1) Multiply $S(z) = z^k [\rho A(z)A(z)^{-1} + B(z)B(z)^{-1}]$
- 2) Obtain $S_r(z)$ (4.3), $Q_s(l, z)$ and $R_s(l, z)$ (4.4).
- 3) Calculate $r_0^0(l)$ and $I(l)$, (4.6) and (4.5).
- 4) Obtain $X_j(z)$ and $C_{j+1}(z)$, (2.8).

This algorithm takes $3.5n^2 + 1.5n - 3$ multiplication and divisions if x_{n-1} and x_n are determined by back substitution, where n is the order of the system.

EXAMPLE 6.

Given $\rho=1$ and

$$A(z) = z^3 - 1.60z^2 + 1.61z - 0.776$$

$$B(z) = z^2 - 0.95z + 0.2$$

Factorize $P(z)$ by means of the program called REFAC2 listed in appendix B.

Step	c_0	c_1	c_2	c_3
0	1.000	0.000	0.000	0.000
1	5.052	-6.732	3.082	-0.776
2	3.089	-3.860	1.736	-0.455
3	2.283	-2.633	1.234	-0.370
4	1.946	-2.187	1.158	-0.395
5	1.818	-2.073	1.194	-0.425
6	1.782	-2.058	1.219	-0.435
7	1.775	-2.061	1.226	-0.437
8	1.775	-2.062	1.228	-0.437
9	1.775	-2.063	1.228	-0.437
10	1.775	-2.063	1.228	-0.437
11	1.775	-2.063	1.228	-0.437
12	1.775	-2.063	1.228	-0.437

The resultant polynomial is given by

$$P(z) = 1.775z^3 - 2.063z^2 + 1.228z - 0.437$$

The accuracy of this algorithm is not as good as with the previous algorithm but it is acceptable in practice. The result obtained by the reduced version to the same numerical example in section 3 is listed as follows.

step	c_0	c_1	c_2	c_3
0	10.583000	7.937253	4.535573	1.133893
1	7.424470	6.536308	4.936104	1.472308
2	6.351079	6.175473	5.642726	1.829136
3	6.019774	6.039279	5.977029	1.984860
4	5.994448	5.998134	6.004982	2.001781
5	6.000621	5.999140	5.998795	1.999791
6	6.000024	6.000298	6.000184	1.999992
7	5.999967	5.999946	5.999983	2.000011
8	6.000010	6.000007	6.000001	1.999997
9	5.999997	6.000000	6.000001	2.000001
10	6.000000	5.999999	6.000001	2.000000
11	6.000000	6.000000	6.000000	2.000000
12	6.000000	5.999997	6.000000	2.000000

5. REFERENCES

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5. Kucera V. (1979): Discrete Linear Control. The Polynomial Equation Approach. Academia Prague.
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Program factorization;

```
{ File is called REFAC1.
  Author Z.Y.Zhou.
  Date   Apr.81. }
```

The program uses Newton's iteration and recursive formulae of integral I (1) to perform the spectral factorization.

$$P(z)*P(z)^{-1} = r*A(z)*A(z)^{-1} + B(z)*B(z)^{-1}.$$

The recursive relationship is given by

$$C(z)*X(z)^{-1} + X(z)*C(z)^{-1} = P(z)*P(z)^{-1}$$

$$C_{i+1}(z) = (C_i(z) + X_i(z)) / 2$$

where i indicates the i-th iteration.

The solution of X(z) is obtained by

$$X = 2*c \# I(i) + 2*c \# I(i-1) + \dots + c \# I(0)$$

where I (1) is an integral of function $f(z)$ along the unit circle

$$f(z) = P_k(z)*P_k(z)^{-1} / (C_k(z)*C_k(z)^{-1})$$

```
const n=10;
```

```
  m=50;
```

```
  l=8;
```

```
  eps=0.001;
```

```
var a,b,t,bt,ct,cr,x:array[0..n] of real;
```

```
  c:array[0..m,0..n] of real;
```

```
  qa,qb,int,fr,frb:array[0..l] of real;
```

```
  ra,rb:array[0..l,0..n] of real;
```

```
  na,ni,la,i,j,s,p:integer;
```

```
  stab:array[0..m] of integer;
```

```
  fa,fb,fc,r:real;
```

```
  ch:char;
```

```
  filename:array[1..n] of char;
```

```
{-----Input}
```

```
Procedure Input;
```

```
{ Input Na -- degree of A(z);
```

```
  A[i] -- element of A(z);
```

```
  Ni -- maximum number of iteration;
```

```
  filename -- the name of a file for store results. }
```

```
begin
```

```
  writeln('Input Ni (the number of iteration) and filename.');
```

```
  read(ni,filename);
```

```
  writeln('Input Na (the degree of A(z))');
```

```
  read(na);
```

```
  repeat
```

```
    writeln('Input A[i]');
```

```
    for i:=0 to na do read(a[i]);
```

```
    writeln('Input B[i]');
```

```

for i:=0 to na do read(b[i]);
writeln('Input r (the weighting coefficient)');
read(r);
writeln('Please check A[i],rewrite?');
repeat read(ch) until ch<>' ';
until ch<>'Y';
end; { of input }

```

```

{-----Initialize}

```

```

Procedure Initialize;

```

```

begin
  writeln(' Set initial C[z] ?');
  repeat read(ch) until ch<>' ';
  if ch='Y' then
    for i:=0 to na do read(c[0,i])
  else begin
    for i:=1 to na do c[0,i]:=0;
    c[0,0]:=1;
  end;
  la:=na-2;
  for i:=0 to ni do stab[i]:=0;
end; { of initialize }

```

```

{-----Polydivision}

```

```

Procedure Polydivision(k:integer);

```

```

begin
  qa[0]:=a[0]/c[k,0];
  qb[0]:=b[0]/c[k,0];
  for i:=1 to na do begin
    ra[0,i]:=a[i]-qa[0]*c[k,i];
    rb[0,i]:=b[i]-qb[0]*c[k,i];
  end;
  int[0]:=0;
  if la>0 then
    for s:=1 to la do begin
      qa[s]:=ra[s-1,1]/c[k,0];
      qb[s]:=rb[s-1,1]/c[k,0];
      ra[s-1,na+1]:=0;
      rb[s-1,na+1]:=0;
      for i:=1 to na do begin
        ra[s,i]:=ra[s-1,i+1]-qa[s]*c[k,i];
        rb[s,i]:=rb[s-1,i+1]-qb[s]*c[k,i];
      end;
      ra[s,0]:=0;
      rb[s,0]:=0;
      int[s]:=r*qa[s]*a[0]+qb[s]*b[0];
    end;
  end;
end; { of polydivision }

```

```

{-----Iteration}

```

```

Procedure Iteration(k:integer);

```

```

var crm,int1:real;
    laa:integer;
begin
  for i:=0 to na do begin
    ct[i]:=c[k,i];
    at[i]:=a[i];
    bt[i]:=b[i];
  end;
  for j:=0 to na-1 do begin
    int1:=r*at[na-j]*at[na-j]+bt[na-j]*bt[na-j];
  end;

```

```

int[O]:=int[O]+int1/ct[O];
if la>0 then for s:=1 to la do begin
    int1:=r*at[na-j]*ra[s,na-j]+bt[na-j]*rb[s,na-j];
    int[s]:=int[s]+int1/ct[O];
end;
for i:=0 to na-j do cr[i]:=ct[na-j-i];
if cr[na-j]<>0 then crm:=cr[na-j] else crm:=eps;
fc:=ct[na-j]/crm;
fa:=at[na-j]/crm;
fb:=bt[na-j]/crm;
if la>0 then for s:=1 to la do begin
    fra[s]:=ra[s,na-j]/crm;
    frb[s]:=rb[s,na-j]/crm;
end;
for i:=0 to na-j-1 do begin
    ct[i]:=ct[i]-fc*cr[i];
    at[i]:=at[i]-fa*cr[i];
    bt[i]:=bt[i]-fb*cr[i];
    if la>0 then for s:=1 to la do begin
        ra[s,i]:=ra[s,i]-fra[s]*cr[i];
        rb[s,i]:=rb[s,i]-frb[s]*cr[i];
    end;
end;

if ct[O]<0 then stab[k]:=stab[k]-1;
if j=na-1 then begin
    int1:=r*at[na-j-1]*at[na-j-1]+bt[na-j-1]*bt[na-j-1];
    int[O]:=int[O]+int1/ct[O];
    if la>0 then for s:=1 to la do begin
        int1:=r*at[na-j-1]*ra[s,na-j-1]+bt[na-j-1]*rb[s,na-j-1];
        int[s]:=int[s]+int1/ct[O];
    end;
end;
end;

if la<0 then laa:=0 else laa:=la;
for s:=0 to laa do begin
    int[s]:=int[s]/c[k,O];
    x[s]:=c[k,s]*int[O];
    if (la>0) and (s>0) then
        for i:=1 to s do x[s]:=x[s]+2*c[k,s-i]*int[i];
    end;
    x[na]:=(2*(r*a[O]*a[na]+b[O]*b[na])-c[k,na]*x[O])/c[k,O];
    if na>1 then begin
        x[na-1]:=2*(r*(a[O]*a[na-1]+a[1]*a[na]+b[O]*b[na-1]+b[1]*b[na]));
        if na>2 then
            x[na-1]:=(x[na-1]-c[k,na-1]*x[O]-c[k,na]*x[1]-c[k,1]*x[na])/c[k,O]
        else x[1]:=(x[na-1]-c[k,1]*x[O]-c[k,1]*x[na])/(c[k,O]+c[k,2]);
    end;
end; { of iteration }

{-----Store}
Procedure Store;
var len:integer;
    outfile:file of char;
begin
    len:=-1;
    rewrite(outfile,filename,'dat',len);
    if len=-1 then writeln('illfile');
    writeln(outfile,'Spectral Factorization:');
    write(outfile,' ');

```

```

for i:=0 to na do write(outfile,'  [' ,i:2,'] ');
writeln(outfile); writeln(outfile);
write(outfile,' A[z] ');
for i:=0 to na do write(outfile,a[i]:8:4);
writeln(outfile);
write(outfile,' B[z] ');
for i:=0 to na do write(outfile,b[i]:8:4);
writeln(outfile); writeln(outfile);
writeln(outfile,' r= ',r:8:4);
writeln(outfile);
for j:=0 to ni do begin
  write(outfile,j:6);
  for i:=0 to na do write(outfile,c[j,i]:8:4);
  if stab[j]<0 then write(' unstable ');
  writeln(outfile);
end;
close(outfile);
end; { of store }

{=====Code of main program}
begin
  input;
  initialize;
  for p:=0 to ni do begin
    polydivision(p);
    iteration(p);
    for i:=0 to na do c[p+1,i]:=(c[p,i]+x[i])/2;
  end;
  store;
end. { of main program }

```

Program factorization;

{ File is called REFAC2.

Author Z.Y.Zhou.

Date Apr.81.

The program uses Newton's iteration and recursive fomulae of integral I (1) to perform the spectral factorization.

$$P(z)*P(z) = r*A(z)*A(z)^{-1} + B(z)*B(z)^{-1} \\ = S(z)*z^{-n}$$

The recursive relationship is given by

$$C(z)*X(z) + X(z)*C(z)^{-1} = P(z)*P(z)^{-1}$$

$$C^{i+1}(z) = (C^i(z) + X^i(z)) / 2$$

where i indicates the i-th iteration.

$$P(z) = \lim_i C^i(z)$$

The solution of X(z) is obtained by

$$x = 2*c \sum_{k=0}^i I(k) + 2*c \sum_{k=1}^i I(i-1) + \dots + c \sum_{k=1}^i I(0)$$

where I (1) is an integral of function $f(z)$ along the unit circle

$$f(z) = S(z)*z^{-k} / (C(z)*C(z)^{-1})$$

const n=10;

m=50;

eps=0.001;

var a,b,s,r,x,q,int:array[0..n] of real;

c:array[0..m,0..n] of real;

rrs:array[0..n,0..n] of real;

na,ni,i,j,l,p:integer;

stab:array[0..m] of integer;

r:real;

ch:char;

filename:array[1..n] of char;

{-----Input}

Procedure Input;

{ Input Na -- degree of A(z);

A[i] -- element of A(z);

Ni -- maximum mumber of iteration;

filename -- the name of a file for store results. }

begin

writeln('Input Ni (the number of iteration) and filename.');

read(ni,filename);

writeln('Input Na (the degree of A(z))');

read(na);

repeat

writeln('Input A[i]');

```

for i:=0 to na do read(a[i]);
writeln('Input B[i]');
for i:=0 to na do read(b[i]);
writeln('Input r (the weighting coefficient)');
read(r);
writeln('Please check A[i],rewrite?');
repeat read(ch) until ch<>' ';
until ch<>'y';
end; { of input }

```

```

{-----Initialize}

```

```

Procedure Initialize;
begin
  writeln(' Set initial C[z] ?');
  repeat read(ch) until ch<>' ';
  if ch='y' then
    for i:=0 to na do read(c[0,i])
    else begin
      for i:=1 to na do c[0,i]:=0;
      c[0,0]:=1;
    end;
    for i:=0 to ni do stab[i]:=0;
  end; { of initialize }

```

```

{-----polymultiply}

```

```

Procedure polymultiply;
var aa,bb:array[0..n] of real;
begin
  for i:=0 to na do begin
    aa[i]:=0;
    bb[i]:=0;
    for j:=i to na do begin
      aa[i]:=aa[i]+a[j-i]*a[j];
      bb[i]:=bb[i]+b[j-i]*b[j];
    end;
    s[na-i]:=r*aa[i]+bb[i];
  end;
  end; { of polymultiply }

```

```

{-----polyfactor}

```

```

Procedure Polyfactor(k:integer);
var sq:array[0..n] of real;
begin
  sq[0]:=s[0]/c[k,0];
  for i:=1 to na-1 do begin
    sq[i]:=sq[i];
    for j:=1 to i do
      sq[i]:=sq[i]-sq[i-j]*c[k,j];
    sq[i]:=sq[i]/c[k,0];
    write(sq[i]:8:4);
  end;
  for i:=0 to na-1 do begin
    sr[i]:=s[na-i];
    for j:=0 to na-i-1 do
      sr[i]:=sr[i]-sq[j+i]*c[k,na-j];
    end;
    sr[na]:=s[0];
  end; { of polyfactor }

```

```

{-----Polydivision}

```

```

Procedure Polydivision(k:integer);

```

```

begin
  q[0]:=sr[0]/c[k,0];
  for i:=1 to na do
    rrs[0,i]:=sr[i]-q[0]*c[k,i];
  int[0]:=q[0];
  for l:=1 to na do begin
    q[l]:=rrs[l-1,1]/c[k,0];
    rrs[l-1,na+1]:=0;
    for i:=1 to na do
      rrs[l,i]:=rrs[l-1,i+1]-q[l]*c[k,i];
    int[l]:=q[l];
  end;
end;
endif of polydivision >

```

```

{-----Iteration}

```

```

Procedure Iteration(k:integer);
var cr,f,af:array[0..n] of real;
ct:array[0..n,0..n] of real;
int1:real;
begin
  for i:=0 to na do
    ct[0,i]:=c[k,i];
  for j:=0 to na-1 do begin
    for i:=0 to na-j do cr[i]:=ct[j,na-j-i];
    f[j]:=ct[j,na-j]/cr[na-j];
    for i:=0 to na-j-1 do
      ct[j+1,i]:=ct[j,i]-f[j]*cr[i];
    if ct[j,0]<0 then stab[k]:=stab[k]-1;
  end;
end;

```

```

  af[l]:=-f[na-1];
  for i:=2 to na do
    for j:=1 to i-1 do
      af[i]:=-f[na-i]-af[i-j]*ct[na-i,j]/ct[na-i,0];
    for l:=0 to na do begin
      int1:=0;
      for j:=1 to na do
        int1:=int1+af[j]*rrs[l,j];
      int1:=int1/ct[na,0];
      int[l]:=int[l]+int1;
    end;
    for l:=0 to na do begin
      int[l]:=int[l]/c[k,0];
      x[l]:=c[k,l]*int[0];
      for i:=1 to l do
        x[l]:=x[l]+2*c[k,l-i]*int[i];
      end;
    end;
  end; { of iteration >

```

```

{-----Store}

```

```

Procedure Store;
var len:integer;
    outfile:file of char;
begin
  len:=1;
  rewrite(outfile,filename,'dat',len);
  if len=-1 then writeln('illfile');
  writeln(outfile,'Spectral Factorization:');
  write(outfile,
    ' ');
  for i:=0 to na do write(outfile,'  ',i:2,' ');
  writeln(outfile); writeln(outfile);
end;

```

```

write(outfile,' A[z] ');
for i:=0 to na do write(outfile,a[i]:8:4);
writeln(outfile);
write(outfile,' B[z] ');
for i:=0 to na do write(outfile,b[i]:8:4);
writeln(outfile); writeln(outfile);
writeln(outfile,' r= ',r:8:4);
writeln(outfile);
for j:=0 to ni do begin
  write(outfile,j:6);
  for i:=0 to na do write(outfile,c[j,i]:8:4);
  if stab[j]<0 then write(' unstable ');
  writeln(outfile);
end;
close(outfile);
end; { of store }

=====Code of main program}
begin
  input;
  polymultiply;
  initialize;
  for p:=0 to ni do begin
    polyfactor(p);
    polydivision(p);
    iteration(p);
    for i:=0 to na do c[p+1,i]:=(c[p,i]+x[i])/2;
  end;
  store;
end. { of main program }

```