

# Pacific Journal of Mathematics

**AN OPTIMUM CUBICALLY CONVERGENT ITERATIVE  
METHOD OF INVERTING A LINEAR BOUNDED OPERATOR  
IN HILBERT SPACE**

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# AN OPTIMUM CUBICALLY CONVERGENT ITERATIVE METHOD OF INVERTING A LINEAR BOUNDED OPERATOR IN HILBERT SPACE

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1. In paper [1] we considered a power series method of inverting a linear bounded operator in Hilbert space. This method is actually an iterative method with the same speed of convergence as a geometric progression. A product of two linear operators we shall call briefly a multiplication. Thus, in general, a power series approximative method has the following two properties:

- (1) at each iteration we use one multiplication;
- (2) the convergence is linear.

In paper [2] we considered an iterative method of inverting an arbitrary linear bounded operator in a Hilbert space. This method requires two multiplications at each iteration step, and the convergence is quadratic. In the present paper we give an iterative method of inverting an arbitrary linear bounded operator in a Hilbert space. This method requires three multiplications at each iteration step and is cubically convergent. Thus, the quadratically convergent method which requires two multiplications at each iteration step may be called the iterative hyperpower method of order two. Analogously, the cubically convergent iterative method which requires three multiplications at each iteration step may be called the iterative hyperpower method of order three. The following two problems arise now in a natural way:

- (1) Is it possible to construct an iterative hyperpower method of any degree?
- (2) To give a comparison of the hyperpower methods of different degrees, and to answer the question whether there exists an optimum method. As a criterion for a hyperpower method to be better we can assume the following:

The method  $I$  is better than the method  $II$  if after some iteration steps using the same amount of multiplications for both methods, the method  $I$  gives better accuracy. In this paper we construct a certain class of iterative hyperpower methods and for this class the answers to both questions mentioned above is positive. It turns out that the optimum method of this class is the iterative hyperpower method of degree three.

Let  $A$  be a linear (i.e. additive and homogeneous) bounded operator with the domain and the range in a Banach space  $X$ .

Let us assume that the operator  $A$  is non-singular, i.e.  $A$  has an

inverse  $A^{-1}$  defined on the space  $X$ . Let us suppose that the linear bounded operator  $R_1$  is an approximate reciprocal of  $A$ . Suppose also that  $R_1$  satisfies the following condition

$$(1) \quad \| I - AR_1 \| = a < 1 ,$$

where  $I$  is the identity mapping of  $X$

Let  $p$  be any positive integer such that  $p \geq 2$ . We shall construct an iterative hyperpower method of degree  $p$  with the following property

$$(2) \quad I - AR_{n+1} = (I - AR_n)^p ,$$

where  $(R_n)$  is the sequence of the approximate inverses of  $A$ . It is easy to see that this sequence can be defined as follows

$$(3) \quad R_{n+1} = R_n(I + T_n + T_n^2 + \dots + T_n^{p-1}) ,$$

where

$$(4) \quad T_n = I - AR_n , \quad n = 1, 2, \dots .$$

Multiplying both sides in (3) by  $A$  we get by (4)

$$AR_{n+1} = (I - T_n)(I + T_n + T_n^2 + \dots + T_n^{p-1}) = I - T_n^p .$$

Hence we obtain the relationship (2).

Thus, we have the following theorem.

**THEOREM 1.** *The sequence of the approximate inverses  $R_n$  defined by formula (3) converges in the norm of operators toward the inverse of the non-singular operator  $A$ , provided that  $R_1$  satisfies condition (1). The error estimate is given by the formula*

$$(5) \quad \| A^{-1} - R_{n+1} \| \leq \| A^{-1} \| a^{p^n}$$

or

$$(6) \quad \| A^{-1} - R_{n+1} \| \leq \| R_1 \| \frac{a^{p^n}}{1 - a}$$

*Proof.* Formula (2) gives by induction

$$(7) \quad AR_{n+1} = I - T_1^{p^n} .$$

Hence we get by (7)

$$(8) \quad R - R_{n+1} = RT_1^{p^n}$$

or

$$(9) \quad R - R_{n+1} = R_1(I - T_1)^{-1}T_1^{p^n} .$$

Formula (5) follows from (8) and formula (6) follows from (9).

For  $p = 2$  formula (3) yields

$$(10) \quad R_{n+1} = R_n(2I - AR_n) .$$

This case was considered in [23]. For  $p = 3$  we get

$$(11) \quad R_{n+1} = R_n(I + (I - AR_n) + (I - AR_n)^2)$$

or

$$(12) \quad R_{n+1} = R_n(3I - 3AR_n + (AR_n)^2)$$

Thus, we have a class of methods with the property (2).

The question is now if there is an optimum method in this class of methods. To compare two methods we shall use the criterion mentioned above, i.e. the method is better if using the same number of multiplications gives a better accuracy.

Let  $p$  and  $q$  be two different positive integers. Consider the correspondings methods  $M_p$  and  $M_q$  defined by the formula (3). At each iteration step the method  $M_p$  takes  $p$  multiplications and the method  $M_q$  takes  $q$  multiplications in the sense defined above. Suppose that after a certain number of iteration steps which is different for both methods we get the same number of multiplications which is equal to

$$(13) \quad mp = nq .$$

Then in virtue of (5) the accuracy of the methods  $M_p$  and  $M_q$  is given by the exponents  $p^m$  and  $q^n$  respectively. Suppose that

$$p^m > q^n .$$

Then we have by (13)

$$p^m > q^s ,$$

where

$$s = \frac{mp}{q} .$$

Hence, we have

$$(14) \quad p^{1/p} > q^{1/q} .$$

The inequality (14) shows that we obtain the optimum method  $M_p$  for  $p$  such that the function  $p^{1/p}$  ( $p = 2, 3, \dots$ ) achieves its maximum. This is the case when  $p = 3$  since the maximum of the function

$$y = x^{1/x} , \quad x > 0$$

is attained at  $x = e$ .

2. We shall now apply Theorem 1 in order to find the approximate inverse of a linear bounded operator in a Hilbert space. Thus, we suppose that  $X$  is a Hilbert space  $H$  and  $A$  is a non-singular linear bounded operator with the domain and the range in  $H$ .

Let us begin with the case when  $A$  is a self-adjoint and positive definite operator, or, more precisely

$$A^* = A ,$$

where  $A^*$  is the adjoint of  $A$ , and  $A$  satisfies the condition

$$m(x, x) \leq (Ax, x) \leq M(x, x) ,$$

where  $0 < m < M$ , and  $m, M$  are the minimum and maximum eigenvalues of  $A$  respectively.

Consider the linear operator.

$$T_\alpha = I - \alpha A , \quad 0 < \alpha < 2/M .$$

In virtue of the critical value theorem<sup>1</sup> we have

$$(13) \quad \frac{M - m}{M + m} \leq \| T_\alpha \| = \alpha_\alpha < 1 \quad \text{if } 0 < \alpha < 2/M .$$

The minimum of the norm  $\| T_\alpha \|$  is equal to

$$(14) \quad \alpha_c = \| T_{\alpha_c} \| = \frac{M - m}{M + m}$$

and is reached precisely at the critical value  $\alpha_c$  of  $A$ , i.e. for

$$\alpha = \alpha_c = \frac{2}{M + m} .$$

Thus, we get the following theorem.

**THEOREM 2.** *Let us suppose that  $A$  is a self-adjoint positive defined linear operator. If*

$$(15) \quad R_1 = \alpha I \quad \text{for } 0 < \alpha < 2/M ,$$

*then the sequence of operators  $R_n$  determined by the iterative process in (3) converges in the norm of the operators toward the inverse of  $A$ . The error estimate is given by the following formula*

$$(16) \quad \| A^{-1} - R_n \| \leq \frac{1}{m} \alpha_\alpha^n$$

<sup>1</sup> See [1], [2]

or

$$(17) \quad \|A^{-1} - R_n\| \leq \frac{\alpha}{1 - a_\alpha} a_\alpha^{p^n},$$

where  $a_\alpha = \|T_\alpha\|$ . The convergence is best for the critical value of  $A$ , i.e. for  $\alpha = \alpha_c = 2/M + m$ . In this case  $a_\alpha$  in formulae (16) and (17) should be replaced by  $a_c$  defined in (14).

Putting  $p = 3$  in Theorem 2 we get the theorem for the optimum method. Thus, we have

**COROLLARY 1.** *The iterative process defined by the formula (11) or (12) converges cubically toward the inverse of  $A$  provided that  $R_1$  is defined by (14). The error estimate is given by formula (16) or (17), where  $p = 3$ . The convergence is best for the critical value of  $A$ , i.e. for  $\alpha = \alpha_c = 2/M + m$ . In this case  $a_\alpha$  in formulae (16) and (17) should be replaced by  $a_c$  defined in (14).*

**REMARK 1.** The convergence of the iterative process is uniform with respect to  $\alpha$  for any closed interval contained in the interval  $0 < \alpha < 2/M$ . Let us observe that  $\alpha$  in (15) can be replaced by any number  $1/K$ , where  $K$  is greater than  $\|A\|$ . However, the convergence is faster when  $K$  is smaller. If the operator  $A$  is defined by a matrix

$$(18) \quad A = (a_{ij}) \quad i, j = 1, 2, \dots, k$$

satisfying the conditions of Theorem 2, then  $K$  can be replaced by any of the following numbers

$$(19) \quad \max_i \sum_{j=1}^k |a_{ij}|; \quad \max_j \sum_{i=1}^k |a_{ij}|; \quad \left( \sum_{i,j=1}^k |a_{ij}|^2 \right)^{1/2}.$$

However, the convergence is faster when  $K$  is smaller.

3. We shall now consider the general case when  $A$  is an arbitrary non-singular linear bounded operator in  $H$ .

Since the operator  $AA^*$  is self-adjoint and positive definite, we have the following inequalities

$$m^2(x, x) \leq (AA^*x, x) \leq M^2(x, x),$$

where  $0 < m^2 < M^2$  and  $m^2, M^2$  are the minimum and the maximum eigenvalues of  $AA^*$  respectively.

Let us consider the linear operator

$$T_\alpha = I - \alpha AA^*, \quad 0 < \alpha < 2/M^2.$$

Using the same argument as in §2, we get the following inequalities

instead of (13).

$$(20) \quad \frac{M^2 - m^2}{M^2 + m^2} \leq \| T_\alpha \| = a_\alpha < 1 \quad \text{if} \quad 0 < \alpha < 2/M^2 .$$

The minimum of the norm  $\| T_\alpha \|$  is reached at

$$\alpha = \alpha_c = \frac{2}{M^2 + m^2}$$

and is equal to

$$(21) \quad a_c = \| T_{\alpha_c} \| = \frac{M^2 - m^2}{M^2 + m^2} .$$

Thus we obtain the following theorem.

**THEOREM 3.** *If*

$$(22) \quad R_1 = \alpha A^* \quad \text{for} \quad 0 < \alpha < 2/M^2 ,$$

*then the sequence of operators  $R_n$  determined by the iterative process in (3) converges in the norm of the operators toward the inverse of  $A$ . The error estimate is given by the formulae (16) or (17), where  $a_\alpha$  should be replaced by the expression in (18). The convergence is best for*

$$\alpha = \alpha_c = \frac{2}{M^2 + m^2} .$$

*For the error estimate in this case  $a_\alpha$  in formulae (16) and (17) should be replaced by  $a_c$  defined in (21).*

Putting  $p = 3$  in Theorem 3 we get the theorem for the optimum method in general case. Thus we have

**COROLLARY 2.** *If  $R_1$  is determined by (22) then the iterative process defined in (11) or (12) converges cubically toward the inverse of  $A$ . For the error estimate we have the formulae (16) or (17), where  $p = 3$ . The convergence is best for the critical value of  $AA^*$ , i.e. for*

$$\alpha = \alpha_c = \frac{2}{M^2 + m^2} .$$

*In this case  $a_\alpha$  in formulae (16) and (17) should be replaced by  $a_c$  determined in (21).*

**REMARK 2.** The convergence of the iterative process defined by Theorem 3 is uniform with respect to  $\alpha$  for any closed interval contained

in the interval  $0 < \alpha < 2/M^2$ . Let us remark that  $\alpha$  in (22) can be replaced by any number  $1/K$ , where  $K$  is greater than  $\|A\|^2$ . However, the convergence is faster when  $K$  is smaller.

If the operator  $A$  is defined by the non-singular matrix in (18), then for  $K$  we can take any of the numbers in (19) with the matrix  $AA^*$  replacing the matrix  $A$ . We can also take for  $K$  any of the squared numbers in (19).

The table below shows the difference in rate of convergence between the following three method: I, II, III, where

I is the power series method considered in [1] (see page 52)

II is the quadratically convergent defined in (10)

III is the cubically convergent optimum method defined in (11) or (12).

Number of Iterations			Number of Multiplication			Accuracy ( $\alpha < 1$ )		
I	II	III	I	II	III	I	II	III
6	3	2	6	6	6	$\alpha^6$	$\alpha^8$	$\alpha^9$
12	6	4	12	12	12	$\alpha^{12}$	$\alpha^{64}$	$\alpha^{81}$
18	9	6	18	18	18	$\alpha^{18}$	$\alpha^{512}$	$\alpha^{729}$
24	12	8	24	24	24	$\alpha^{24}$	$\alpha^{4096}$	$\alpha^{6561}$

## REFERENCES

1. M. Altman, *Inversion of non-singular linear bounded operators in Hilbert space with application to matrix calculus.*
2. ———, *Inversion of linear bounded operators in Hilbert space with application to matrix calculus.*

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M. Altman, <i>An optimum cubically convergent iterative method of inverting a linear bounded operator in Hilbert space</i> .....	1107
Nesmith Cornett Ankeny, <i>Criterion for <math>r</math>th power residuacity</i> .....	1115
Julius Rubin Blum and David Lee Hanson, <i>On invariant probability measures I</i> .....	1125
Frank Featherstone Bonsall, <i>Positive operators compact in an auxiliary topology</i> .....	1131
Billy Joe Boyer, <i>Summability of derived conjugate series</i> .....	1139
Delmar L. Boyer, <i>A note on a problem of Fuchs</i> .....	1147
Hans-Joachim Bremermann, <i>The envelopes of holomorphy of tube domains in infinite dimensional Banach spaces</i> .....	1149
Andrew Michael Bruckner, <i>Minimal superadditive extensions of superadditive functions</i> .....	1155
Billy Finney Bryant, <i>On expansive homeomorphisms</i> .....	1163
Jean W. Butler, <i>On complete and independent sets of operations in finite algebras</i> .....	1169
Lucien Le Cam, <i>An approximation theorem for the Poisson binomial distribution</i> .....	1181
Paul Civin, <i>Involutions on locally compact rings</i> .....	1199
Earl A. Coddington, <i>Normal extensions of formally normal operators</i> .....	1203
Jacob Feldman, <i>Some classes of equivalent Gaussian processes on an interval</i> .....	1211
Shaul Foguel, <i>Weak and strong convergence for Markov processes</i> .....	1221
Martin Fox, <i>Some zero sum two-person games with moves in the unit interval</i> .....	1235
Robert Pertsch Gilbert, <i>Singularities of three-dimensional harmonic functions</i> .....	1243
Branko Grünbaum, <i>Partitions of mass-distributions and of convex bodies by hyperplanes</i> .....	1257
Sidney Morris Harmon, <i>Regular covering surfaces of Riemann surfaces</i> .....	1263
Edwin Hewitt and Herbert S. Zuckerman, <i>The multiplicative semigroup of integers modulo <math>m</math></i> .....	1291
Paul Daniel Hill, <i>Relation of a direct limit group to associated vector groups</i> .....	1309
Calvin Virgil Holmes, <i>Commutator groups of monomial groups</i> .....	1313
James Fredrik Jakobsen and W. R. Utz, <i>The non-existence of expansive homeomorphisms on a closed 2-cell</i> .....	1319
John William Jewett, <i>Multiplication on classes of pseudo-analytic functions</i> .....	1323
Helmut Klingen, <i>Analytic automorphisms of bounded symmetric complex domains</i> .....	1327
Robert Jacob Koch, <i>Ordered semigroups in partially ordered semigroups</i> .....	1333
Marvin David Marcus and N. A. Khan, <i>On a commutator result of Taussky and Zassenhaus</i> .....	1337
John Glen Marica and Steve Jerome Bryant, <i>Unary algebras</i> .....	1347
Edward Peter Merkes and W. T. Scott, <i>On univalence of a continued fraction</i> .....	1361
Shu-Teh Chen Moy, <i>Asymptotic properties of derivatives of stationary measures</i> .....	1371
John William Neuberger, <i>Concerning boundary value problems</i> .....	1385
Edward C. Posner, <i>Integral closure of differential rings</i> .....	1393
Marian Reichaw-Reichbach, <i>Some theorems on mappings onto</i> .....	1397
Marvin Rosenblum and Harold Widom, <i>Two extremal problems</i> .....	1409
Morton Lincoln Slater and Herbert S. Wilf, <i>A class of linear differential-difference equations</i> .....	1419
Charles Robson Storey, Jr., <i>The structure of threads</i> .....	1429
J. François Treves, <i>An estimate for differential polynomials in <math>\partial/\partial z_1, \dots, \partial/\partial z_n</math></i> .....	1447
J. D. Weston, <i>On the representation of operators by convolutions integrals</i> .....	1453
James Victor Whittaker, <i>Normal subgroups of some homeomorphism groups</i> .....	1469