D05ABF – NAG Fortran Library Routine Document

Note. Before using this routine, please read the Users' Note for your implementation to check the interpretation of bold italicised terms and other implementation-dependent details.

1 Purpose

D05ABF solves any linear non-singular Fredholm integral equation of the second kind with a smooth kernel.

2 Specification

```
 SUBROUTINE D05ABF(K, G, LAMBDA, A, B, ODOREV, EV, N, CM, F1, WK,
1                  NMAX, NT2P1, F, C, IFAIL)
 INTEGER           N, NMAX, NT2P1, IFAIL
 real              K, G, LAMBDA, A, B, CM(NMAX,NMAX), F1(NMAX,1),
1                  WK(2,NT2P1), F(N), C(N)
 LOGICAL           ODOREV, EV
 EXTERNAL          K, G
```

3 Description

This routine uses the method of El-gendi [2] to solve an integral equation of the form

$$f(x) - \lambda \int_a^b k(x,s) f(s)\, ds = g(x)$$

for the function $f(x)$ in the range $a \le x \le b$.

An approximation to the solution $f(x)$ is found in the form of an n term Chebyshev-series $\sum_{i=1}^{n}{}' c_i T_i(x)$, where $'$ indicates that the first term is halved in the sum. The coefficients c_i, for $i = 1, 2, \ldots, n$, of this series are determined directly from approximate values f_i, for $i = 1, 2, \ldots, n$, of the function $f(x)$ at the first n of a set of $m+1$ Chebyshev points

$$x_i = \frac{1}{2}(a + b + (b-a) \times \cos[(i-1) \times \pi/m]), \qquad i = 1, 2, \ldots, m+1.$$

The values f_i are obtained by solving a set of simultaneous linear algebraic equations formed by applying a quadrature formula (equivalent to the scheme of Clenshaw and Curtis [1]) to the integral equation at each of the above points.

In general $m = n-1$. However, advantage may be taken of any prior knowledge of the symmetry of $f(x)$. Thus if $f(x)$ is symmetric (i.e., even) about the mid-point of the range (a, b), it may be approximated by an even Chebyshev-series with $m = 2n-1$. Similarly, if $f(x)$ is anti-symmetric (i.e., odd) about the mid-point of the range of integration, it may be approximated by an odd Chebyshev-series with $m = 2n$.

4 References

[1] Clenshaw C W and Curtis A R (1960) A method for numerical integration on an automatic computer *Numer. Math.* **2** 197–205

[2] El–Gendi S E (1969) Chebyshev solution of differential, integral and integro-differential equations *Comput. J.* **12** 282–287

5 Parameters

1: K — ***real*** FUNCTION, supplied by the user. *External Procedure*

K must compute the value of the kernel $k(x,s)$ of the integral equation over the square $a \leq x \leq b$, $a \leq s \leq b$.

Its specification is:

```
real FUNCTION K(X, S)
real            X, S
```

1: X — ***real*** *Input*

2: S — ***real*** *Input*

On entry: the values of x and s at which $k(x,s)$ is to be calculated.

K must be declared as EXTERNAL in the (sub)program from which D05ABF is called. Parameters denoted as *Input* must **not** be changed by this procedure.

2: G — ***real*** FUNCTION, supplied by the user. *External Procedure*

G must compute the value of the function $g(x)$ of the integral equation in the interval $a \leq x \leq b$.

Its specification is:

```
real FUNCTION G(X)
real            X
```

1: X — ***real*** *Input*

On entry: the value of x at which $g(x)$ is to be calculated.

G must be declared as EXTERNAL in the (sub)program from which D05ABF is called. Parameters denoted as *Input* must **not** be changed by this procedure.

3: LAMBDA — ***real*** *Input*

On entry: the value of the parameter λ of the integral equation.

4: A — ***real*** *Input*

On entry: the lower limit of integration, a.

5: B — ***real*** *Input*

On entry: the upper limit of integration, b.

Constraint: B > A.

6: ODOREV — LOGICAL *Input*

On entry: indicates whether it is known that the solution $f(x)$ is odd or even about the mid-point of the range of integration. If ODOREV is .TRUE. then an odd or even solution is sought depending upon the value of EV.

7: EV — LOGICAL *Input*

On entry: EV is ignored if ODOREV is .FALSE. Otherwise, if EV is .TRUE., an even solution is sought, whilst if EV is .FALSE., an odd solution is sought.

8: N — INTEGER *Input*

On entry: the number of terms in the Chebyshev-series which approximates the solution $f(x)$.

9: CM(NMAX,NMAX) — ***real*** array *Workspace*

10: F1(NMAX,1) — ***real*** array *Workspace*

11: WK(2,NT2P1) — ***real*** array *Workspace*

12: NMAX — INTEGER *Input*

On entry: the first dimension of the arrays CM and F1 as declared in the (sub)program from which D05ABF is called.

Constraint: NMAX $\geq$ N.

13: NT2P1 — INTEGER *Input*

On entry: the value $2 \times \mathrm{N} + 1$.

14: F(N) — ***real*** array *Output*

On exit: the approximate values f_i, for $i = 1, 2, \ldots, \mathrm{N}$, of the function $f(x)$ at the first N of $\mathrm{M} + 1$ Chebyshev points (see Section 3).

If ODOREV is .TRUE., then $\mathrm{M} = 2 \times \mathrm{N} - 1$ if EV is .TRUE. and $\mathrm{M} = 2 \times \mathrm{N}$ if EV is .FALSE.; otherwise $\mathrm{M} = \mathrm{N} - 1$.

15: C(N) — ***real*** array *Output*

On exit: the coefficients c_i, for $i = 1, 2, \ldots, \mathrm{N}$, of the Chebyshev-series approximation to $f(x)$. When ODOREV is .TRUE., this series contains polynomials of even order only or of odd order only, according to EV being .TRUE. or .FALSE. respectively.

16: IFAIL — INTEGER *Input/Output*

On entry: IFAIL must be set to 0, -1 or 1. For users not familiar with this parameter (described in Chapter P01) the recommended value is 0.

On exit: IFAIL = 0 unless the routine detects an error (see Section 6).

6 Error Indicators and Warnings

Errors detected by the routine:

IFAIL = 1

A $\geq$ B.

IFAIL = 2

A failure has occurred (in F04AAF unless N = 1) due to proximity to an eigenvalue. In general, if LAMBDA is near an eigenvalue of the integral equation, the corresponding matrix will be nearly singular.

7 Accuracy

No explicit error estimate is provided by the routine but it is possible to obtain a good indication of the accuracy of the solution either

(i) by examining the size of the later Chebyshev coefficients c_i, or
(ii) by comparing the coefficients c_i or the function values f_i for two or more values of N.

8 Further Comments

The time taken by the routine depends upon the value of N and upon the complexity of the kernel function $k(x, s)$.

9 Example

Solve Love's equation:

$$f(x) + \frac{1}{\pi} \int_{-1}^{1} \frac{f(s)}{1 + (x - s)^2} \, ds = 1$$

The example program will solve the slightly more general equation:

$$f(x) - \lambda \int_a^b k(x, s) f(s) \, ds = 1$$

where $k(x, s) = \alpha/(\alpha^2 + (x - s)^2)$. The values $\lambda = -1/\pi, a = -1, b = 1, \alpha = 1$ are used below.

It is evident from the symmetry of the given equation that $f(x)$ is an even function. Advantage is taken of this fact both in the application of D05ABF, to obtain the $f_i \simeq f(x_i)$ and the c_i, and in subsequent applications of C06DBF to obtain $f(x)$ at selected points.

The program runs for N = 5 and N = 10.

9.1 Program Text

Note. The listing of the example program presented below uses bold italicised terms to denote precision-dependent details. Please read the Users' Note for your implementation to check the interpretation of these terms. As explained in the Essential Introduction to this manual, the results produced may not be identical for all implementations.

```
*     D05ABF Example Program Text
*     Mark 14 Revised.  NAG Copyright 1989.
*     .. Parameters ..
      INTEGER          NMAX, NT2P1
      PARAMETER        (NMAX=10,NT2P1=2*NMAX+1)
      INTEGER          NOUT
      PARAMETER        (NOUT=6)
*     .. Scalars in Common ..
      real             ALPHA, W
*     .. Local Scalars ..
      real             A, A1, B, CHEBR, D, E, LAMBDA, S, X
      INTEGER          I, IFAIL, N, SS
      LOGICAL          EV, ODOREV
*     .. Local Arrays ..
      real             C(NMAX), CM(NMAX,NMAX), F(NMAX), F1(NMAX,1),
     +                 WK(2,NT2P1)
*     .. External Functions ..
      real             C06DBF, GE, KE
      EXTERNAL         C06DBF, GE, KE
*     .. External Subroutines ..
      EXTERNAL         D05ABF
*     .. Common blocks ..
      COMMON           /AFRED2/ALPHA, W
*     .. Executable Statements ..
      WRITE (NOUT,*) 'D05ABF Example Program Results'
      WRITE (NOUT,*)
      ODOREV = .TRUE.
      EV = .TRUE.
      LAMBDA = -0.3183e0
      A = -1.0e0
      B = 1.0e0
      ALPHA = 1.0e0
      W = ALPHA*ALPHA
      IF (ODOREV .AND. EV) THEN
         WRITE (NOUT,*) 'Solution is even'
      ELSE
```

```
         IF (ODOREV) WRITE (NOUT,*) 'Solution is odd'
      END IF
      DO 60 N = 5, NMAX, 5
         IFAIL = 1
*
         CALL D05ABF(KE,GE,LAMBDA,A,B,ODOREV,EV,N,CM,F1,WK,NMAX,NT2P1,F,
     +               C,IFAIL)
*
         IF (IFAIL.EQ.0) THEN
            WRITE (NOUT,*)
            WRITE (NOUT,99999) 'Results for N =', N
            WRITE (NOUT,*)
            WRITE (NOUT,*) '  I         F(I)         C(I)'
            DO 20 I = 1, N
               WRITE (NOUT,99998) I, F(I), C(I)
   20       CONTINUE
            WRITE (NOUT,*)
            WRITE (NOUT,*) '     X           F(X)'
            IF (ODOREV) THEN
               IF (EV) THEN
                  SS = 2
               ELSE
                  SS = 3
               END IF
            ELSE
               SS = 1
            END IF
            A1 = 0.5e0*(A+B)
            S = 0.5e0*(B-A)
            X = A1
            IF ( .NOT. ODOREV) THEN
               X = X - 5
            ELSE
               X = A1
            END IF
            D = 1.0e0/S
            S = 0.25e0*S
            E = B + 0.1e0*S
   40       CHEBR = C06DBF((X-A1)*D,C,N,SS)
            WRITE (NOUT,99997) X, CHEBR
            X = X + S
            IF (X.LT.E) GO TO 40
         ELSE
            IF (IFAIL.EQ.1) THEN
               WRITE (NOUT,*)
               WRITE (NOUT,*) 'Failure in D05ABF -'
               WRITE (NOUT,*) 'error in integration limits'
            ELSE
               WRITE (NOUT,*)
               WRITE (NOUT,*) 'Failure in D05ABF -'
               WRITE (NOUT,*) 'LAMBDA near eigenvalue'
            END IF
         END IF
   60 CONTINUE
      STOP
*
99999 FORMAT (1X,A,I3)
99998 FORMAT (1X,I3,F15.5,e15.5)
```

```
99997 FORMAT (1X,F8.4,F15.5)
      END
*
      real FUNCTION KE(X,S)
*     .. Scalar Arguments ..
      real                 S, X
*     .. Scalars in Common ..
      real                 ALPHA, W
*     .. Common blocks ..
      COMMON               /AFRED2/ALPHA, W
*     .. Executable Statements ..
      KE = ALPHA/(W+(X-S)*(X-S))
      RETURN
      END
*
      real FUNCTION GE(X)
*     .. Scalar Arguments ..
      real                 X
*     .. Executable Statements ..
      GE = 1.0e0
      RETURN
      END
```

9.2 Program Data

None.

9.3 Program Results

```
D05ABF Example Program Results

Solution is even

Results for N =  5

  I         F(I)         C(I)
  1        0.75572    0.14152E+01
  2        0.74534    0.49384E-01
  3        0.71729   -0.10476E-02
  4        0.68319   -0.23282E-03
  5        0.66051    0.20890E-04

     X           F(X)
  0.0000        0.65742
  0.2500        0.66383
  0.5000        0.68319
  0.7500        0.71489
  1.0000        0.75572

Results for N = 10

  I         F(I)         C(I)
  1        0.75572    0.14152E+01
  2        0.75336    0.49384E-01
  3        0.74639   -0.10475E-02
  4        0.73525   -0.23275E-03
  5        0.72081    0.19986E-04
  6        0.70452    0.98675E-06
```

```
   7        0.68825   -0.23796E-06
   8        0.67404    0.18581E-08
   9        0.66361    0.24483E-08
  10        0.65812   -0.16527E-09

     X          F(X)
   0.0000       0.65742
   0.2500       0.66384
   0.5000       0.68319
   0.7500       0.71489
   1.0000       0.75572
```