

# NAG Fortran Library Routine Document

## D05ABF

**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, NMAX,
1          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 (1969) 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  $a \leq x \leq b$ .

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  $i = 1, 2, \dots, n$ , of this series are determined directly from approximate values  $f_i$ , for  $i = 1, 2, \dots, n$ , of the function  $f(x)$  at the first  $n$  of a set of  $m + 1$  Chebyshev points

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

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 (1960)) 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

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

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:

<pre> <b>real</b> FUNCTION K(X, S) <b>real</b>          X, S 1:  X – <i>real</i> 2:  S – <i>real</i> On entry: the values of x and s at which k(x, s) is to be calculated. </pre>	<i>Input</i> <i>Input</i>
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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:

<pre> <b>real</b> FUNCTION G(X) <b>real</b>          X 1:  X – <i>real</i> On entry: the value of x at which g(x) is to be calculated. </pre>	<i>Input</i>
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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  $\lambda$  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  $2 \times N + 1$ .
- 14: F(N) – *real* array Output  
*On exit:* the approximate values  $f_i$ , for  $i = 1, 2, \dots, N$ , of the function  $f(x)$  at the first N of  $M + 1$  Chebyshev points (see Section 3).  
 If ODOREV is .TRUE., then  $M = 2 \times N - 1$  if EV is .TRUE. and  $M = 2 \times N$  if EV is .FALSE.; otherwise  $M = N - 1$ .
- 15: C(N) – *real* array Output  
*On exit:* the coefficients  $c_i$ , for  $i = 1, 2, \dots, N$ , 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. Users who are unfamiliar with this parameter should refer to Chapter P01 for details.  
*On exit:* IFAIL = 0 unless the routine detects an error (see Section 6).  
 For environments where it might be inappropriate to halt program execution when an error is detected, the value -1 or 1 is recommended. If the output of error messages is undesirable, then the value 1 is recommended. Otherwise, for users not familiar with this parameter the recommended value is 0. **When the value -1 or 1 is used it is essential to test the value of IFAIL on exit.**

## 6 Error Indicators and Warnings

If on entry IFAIL = 0 or -1, explanatory error messages are output on the current error message unit (as defined by X04AAF).

Errors or warnings detected by the routine:

IFAIL = 1

On entry,  $A \geq B$ .

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           CO6DBF, GE, KE
EXTERNAL         CO6DBF, 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