NAG Library Routine Document

F04BDF

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

F04BDF computes the solution to a real system of linear equations $AX = B$, where A is an n by n symmetric positive definite matrix and X and B are n by r matrices. An estimate of the condition number of A and an error bound for the computed solution are also returned.

2 Specification

```
SUBROUTINE F04BDF (UPLO, N, NRHS, A, LDA, B, LDB, RCOND, ERRBND, IFAIL)

INTEGER             N, NRHS, LDA, LDB, IFAIL
REAL (KIND=nag_wp)  A(LDA,*), B(LDB,*), RCOND, ERRBND
CHARACTER(1)        UPLO
```

3 Description

The Cholesky factorization is used to factor A as $A = U^{\mathrm{T}}U$, if UPLO = 'U', or $A = LL^{\mathrm{T}}$, if UPLO = 'L', where U is an upper triangular matrix and L is a lower triangular matrix. The factored form of A is then used to solve the system of equations $AX = B$.

4 References

Anderson E, Bai Z, Bischof C, Blackford S, Demmel J, Dongarra J J, Du Croz J J, Greenbaum A, Hammarling S, McKenney A and Sorensen D (1999) *LAPACK Users' Guide* (3rd Edition) SIAM, Philadelphia http://www.netlib.org/lapack/lug

Higham N J (2002) *Accuracy and Stability of Numerical Algorithms* (2nd Edition) SIAM, Philadelphia

5 Parameters

1: UPLO – CHARACTER(1) *Input*

On entry: if UPLO = 'U', the upper triangle of the matrix A is stored.

If UPLO = 'L', the lower triangle of the matrix A is stored.

Constraint: UPLO = 'U' or 'L'.

2: N – INTEGER *Input*

On entry: the number of linear equations n, i.e., the order of the matrix A.

Constraint: N $\geq$ 0.

3: NRHS – INTEGER *Input*

On entry: the number of right-hand sides r, i.e., the number of columns of the matrix B.

Constraint: NRHS $\geq$ 0.

4: A(LDA, $*$) – REAL (KIND=nag_wp) array *Input/Output*

Note: the second dimension of the array A must be at least $\max(1,\mathrm{N})$.

On entry: the n by n symmetric matrix A.

If UPLO = 'U', the leading N by N upper triangular part of A contains the upper triangular part of the matrix A, and the strictly lower triangular part of A is not referenced.

If UPLO = 'L', the leading N by N lower triangular part of A contains the lower triangular part of the matrix A, and the strictly upper triangular part of A is not referenced.

On exit: if IFAIL $= 0$ or N $+ 1$, the factor U or L from the Cholesky factorization $A = U^{\mathrm{T}}U$ or $A = LL^{\mathrm{T}}$.

5: LDA – INTEGER *Input*

On entry: the first dimension of the array A as declared in the (sub)program from which F04BDF is called.

Constraint: LDA $\geq \max(1, \mathrm{N})$.

6: B(LDB, $*$) – REAL (KIND=nag_wp) array *Input/Output*

Note: the second dimension of the array B must be at least $\max(1, \mathrm{NRHS})$.

On entry: the n by r matrix of right-hand sides B.

On exit: if IFAIL $= 0$ or N $+ 1$, the n by r solution matrix X.

7: LDB – INTEGER *Input*

On entry: the first dimension of the array B as declared in the (sub)program from which F04BDF is called.

Constraint: LDB $\geq \max(1, \mathrm{N})$.

8: RCOND – REAL (KIND=nag_wp) *Output*

On exit: if IFAIL $= 0$ or N $+ 1$, an estimate of the reciprocal of the condition number of the matrix A, computed as RCOND $= 1/\left(\|A\|_1\|A^{-1}\|_1\right)$.

9: ERRBND – REAL (KIND=nag_wp) *Output*

On exit: if IFAIL $= 0$ or N $+ 1$, an estimate of the forward error bound for a computed solution $\hat{x}$, such that $\|\hat{x} - x\|_1/\|x\|_1 \leq$ ERRBND, where $\hat{x}$ is a column of the computed solution returned in the array B and x is the corresponding column of the exact solution X. If RCOND is less than ***machine precision***, then ERRBND is returned as unity.

10: IFAIL – INTEGER *Input/Output*

On entry: IFAIL must be set to 0, -1 or 1. If you are unfamiliar with this parameter you should refer to Section 3.3 in the Essential Introduction for details.

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, if you are 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.**

On exit: IFAIL $= 0$ unless the routine detects an error or a warning has been flagged (see Section 6).

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 < 0 and IFAIL $\neq -999$

If IFAIL $= -i$, the ith argument had an illegal value.

IFAIL > 0 and IFAIL $\leq$ N

If IFAIL $= i$, the leading minor of order i of A is not positive definite. The factorization could not be completed, and the solution has not been computed.

IFAIL $=$ N $+ 1$

RCOND is less than ***machine precision***, so that the matrix A is numerically singular. A solution to the equations $AX = B$ has nevertheless been computed.

IFAIL $= -99$

An unexpected error has been triggered by this routine. Please contact NAG.

See Section 3.8 in the Essential Introduction for further information.

IFAIL $= -399$

Your licence key may have expired or may not have been installed correctly.

See Section 3.7 in the Essential Introduction for further information.

IFAIL $= -999$

Dynamic memory allocation failed.

See Section 3.6 in the Essential Introduction for further information.

7 Accuracy

The computed solution for a single right-hand side, $\hat{x}$, satisfies an equation of the form

$$(A + E)\hat{x} = b,$$

where

$$\|E\|_1 = O(\epsilon)\|A\|_1$$

and ϵ is the ***machine precision***. An approximate error bound for the computed solution is given by

$$\frac{\|\hat{x} - x\|_1}{\|x\|_1} \leq \kappa(A)\frac{\|E\|_1}{\|A\|_1},$$

where $\kappa(A) = \left\|A^{-1}\right\|_1 \|A\|_1$, the condition number of A with respect to the solution of the linear equations. F04BDF uses the approximation $\|E\|_1 = \epsilon\|A\|_1$ to estimate ERRBND. See Section 4.4 of Anderson *et al.* (1999) for further details.

8 Parallelism and Performance

F04BDF is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

F04BDF makes calls to BLAS and/or LAPACK routines, which may be threaded within the vendor library used by this implementation. Consult the documentation for the vendor library for further information.

Please consult the X06 Chapter Introduction for information on how to control and interrogate the OpenMP environment used within this routine. Please also consult the Users' Note for your implementation for any additional implementation-specific information.

9 Further Comments

The integer allocatable memory required is N, and the real allocatable memory required is 3 × N. Allocation failed before the solution could be computed.

The total number of floating-point operations required to solve the equations $AX = B$ is proportional to $\left(\frac{1}{3}n^3 + n^2r\right)$. The condition number estimation typically requires between four and five solves and never more than eleven solves, following the factorization.

In practice the condition number estimator is very reliable, but it can underestimate the true condition number; see Section 15.3 of Higham (2002) for further details.

The complex analogue of F04BDF is F04CDF.

10 Example

This example solves the equations

$$AX = B,$$

where A is the symmetric positive definite matrix

$$A = \begin{pmatrix} 4.16 & -3.12 & 0.56 & -0.10 \\ -3.12 & 5.03 & -0.83 & 1.18 \\ 0.56 & -0.83 & 0.76 & 0.34 \\ -0.10 & 1.18 & 0.34 & 1.18 \end{pmatrix} \quad \text{and} \quad B = \begin{pmatrix} 8.70 & 8.30 \\ -13.35 & 2.13 \\ 1.89 & 1.61 \\ -4.14 & 5.00 \end{pmatrix}.$$

An estimate of the condition number of A and an approximate error bound for the computed solutions are also printed.

10.1 Program Text

```
    Program f04bdfe

!     F04BDF Example Program Text

!     Mark 25 Release. NAG Copyright 2014.

!     .. Use Statements ..
      Use nag_library, Only: f04bdf, nag_wp, x04caf
!     .. Implicit None Statement ..
      Implicit None
!     .. Parameters ..
      Integer, Parameter               :: nin = 5, nout = 6
!     .. Local Scalars ..
      Real (Kind=nag_wp)               :: errbnd, rcond
      Integer                          :: i, ierr, ifail, lda, ldb, n, nrhs
!     .. Local Arrays ..
      Real (Kind=nag_wp), Allocatable  :: a(:,:), b(:,:)
!     .. Executable Statements ..
      Write (nout,*) 'F04BDF Example Program Results'
      Write (nout,*)
      Flush (nout)
!     Skip heading in data file
      Read (nin,*)
      Read (nin,*) n, nrhs
      lda = n
      ldb = n
      Allocate (a(lda,n),b(ldb,nrhs))
!     Read the upper triangular part of A from data file
      Read (nin,*)(a(i,i:n),i=1,n)

!     Read B from data file
```

```
      Read (nin,*)(b(i,1:nrhs),i=1,n)

!     Solve the equations AX = B for X

!     ifail: behaviour on error exit
!             =0 for hard exit, =1 for quiet-soft, =-1 for noisy-soft
      ifail = 1
      Call f04bdf('Upper',n,nrhs,a,lda,b,ldb,rcond,errbnd,ifail)

      If (ifail==0) Then
!       Print solution, estimate of condition number and approximate
!       error bound

        ierr = 0
        Call x04caf('General',' ',n,nrhs,b,ldb,'Solution',ierr)

        Write (nout,*)
        Write (nout,*) 'Estimate of condition number'
        Write (nout,99999) 1.0E0_nag_wp/rcond
        Write (nout,*)
        Write (nout,*) 'Estimate of error bound for computed solutions'
        Write (nout,99999) errbnd
      Else If (ifail==n+1) Then
!       Matrix A is numerically singular.  Print estimate of
!       reciprocal of condition number and solution
        Write (nout,*)
        Write (nout,*) 'Estimate of reciprocal of condition number'
        Write (nout,99999) rcond
        Write (nout,*)
        Flush (nout)

        ierr = 0
        Call x04caf('General',' ',n,nrhs,b,ldb,'Solution',ierr)

      Else If (ifail>0 .And. ifail<=n) Then
!       The matrix A is not positive definite to working precision
        Write (nout,99998) 'The leading minor of order ', ifail, &
          ' is not positive definite'
      Else
        Write (nout,99997) ifail
      End If

99999 Format (6X,1P,E9.1)
99998 Format (1X,A,I3,A)
99997 Format (1X,' ** F04BDF returned with IFAIL = ',I5)
    End Program f04bdfe
```

10.2 Program Data

```
F04BDF Example Program Data

   4      2                  :Values of N and NRHS

   4.16  -3.12   0.56  -0.10
          5.03  -0.83   1.18
                 0.76   0.34
                        1.18 :End of matrix A

   8.70   8.30
 -13.35   2.13
   1.89   1.61
  -4.14   5.00               :End of matrix B
```

10.3 Program Results

```
 F04BDF Example Program Results

 Solution
             1          2
 1      1.0000     4.0000
 2     -1.0000     3.0000
 3      2.0000     2.0000
 4     -3.0000     1.0000

 Estimate of condition number
        9.7E+01

 Estimate of error bound for computed solutions
        1.1E-14
```