

NAG Library Routine Document

F04CJF

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

F04CJF computes the solution to a complex system of linear equations $AX = B$, where A is an n by n complex Hermitian matrix, stored in packed format 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 F04CJF (UPLO, N, NRHS, AP, IPIV, B, LDB, RCOND, ERBND, &
IFAIL)

INTEGER N, NRHS, IPIV(N), LDB, IFAIL
REAL (KIND=nag_wp) RCOND, ERBND
COMPLEX (KIND=nag_wp) AP(*), B(LDB,*)
CHARACTER(1) UPLO

3 Description

The diagonal pivoting method is used to factor A as $A = UDU^H$, if $UPLO = 'U'$, or $A = LDL^H$, if $UPLO = 'L'$, where U (or L) is a product of permutation and unit upper (lower) triangular matrices, and D is Hermitian and block diagonal with 1 by 1 and 2 by 2 diagonal blocks. 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 Arguments

- 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: AP(*) – COMPLEX (KIND=nag_wp) array Input/Output
Note: the dimension of the array AP must be at least $\max(1, N \times (N + 1)/2)$.
On entry: the n by n Hermitian matrix A , packed column-wise in a linear array. The j th column of the matrix A is stored in the array AP as follows:
 More precisely,
 if UPLO = 'U', the upper triangle of A must be stored with element A_{ij} in $\text{AP}(i + j(j - 1)/2)$ for $i \leq j$;
 if UPLO = 'L', the lower triangle of A must be stored with element A_{ij} in $\text{AP}(i + (2n - j)(j - 1)/2)$ for $i \geq j$.
On exit: if IFAIL ≥ 0 , the block diagonal matrix D and the multipliers used to obtain the factor U or L from the factorization $A = UDU^H$ or $A = LDL^H$ as computed by F07PRF (ZHPTRF), stored as a packed triangular matrix in the same storage format as A .
- 5: IPIV(N) – INTEGER array Output
On exit: if IFAIL ≥ 0 , details of the interchanges and the block structure of D , as determined by F07PRF (ZHPTRF).
 If IPIV(k) > 0 , then rows and columns k and IPIV(k) were interchanged, and d_{kk} is a 1 by 1 diagonal block;
 if UPLO = 'U' and IPIV(k) = IPIV($k - 1$) < 0 , then rows and columns $k - 1$ and $-IPIV(k)$ were interchanged and $d_{k-1:k, k-1:k}$ is a 2 by 2 diagonal block;
 if UPLO = 'L' and IPIV(k) = IPIV($k + 1$) < 0 , then rows and columns $k + 1$ and $-IPIV(k)$ were interchanged and $d_{k:k+1, k:k+1}$ is a 2 by 2 diagonal block.
- 6: B(LDB, *) – COMPLEX (KIND=nag_wp) array Input/Output
Note: the second dimension of the array B must be at least $\max(1, \text{NRHS})$.
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 F04CJF is called.
Constraint: LDB $\geq \max(1, N)$.
- 8: RCOND – REAL (KIND=nag_wp) Output
On exit: if no constraints are violated, an estimate of the reciprocal of the condition number of the matrix A , computed as $\text{RCOND} = 1 / (\|A\|_1 \|A^{-1}\|_1)$.
- 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 $\|\hat{x} - x\|_1 / \|x\|_1 \leq \text{ERRBND}$, 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 argument you should refer to Section 3.4 in How to Use the NAG Library and its Documentation 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 argument, 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 \leq N

Diagonal block $\langle value \rangle$ of the block diagonal matrix is zero. The factorization has been completed, but the solution could not be computed.

IFAIL = N + 1

A solution has been computed, but RCOND is less than *machine precision* so that the matrix A is numerically singular.

IFAIL = -1

On entry, UPLO \neq 'U' or 'L': UPLO = $\langle value \rangle$.

IFAIL = -2

On entry, N = $\langle value \rangle$.
Constraint: N \geq 0.

IFAIL = -3

On entry, NRHS = $\langle value \rangle$.
Constraint: NRHS \geq 0.

IFAIL = -7

On entry, LDB = $\langle value \rangle$ and N = $\langle value \rangle$.
Constraint: LDB \geq max(1, N).

IFAIL = -99

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

See Section 3.9 in How to Use the NAG Library and its Documentation for further information.

IFAIL = -399

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

See Section 3.8 in How to Use the NAG Library and its Documentation for further information.

IFAIL = -999

Dynamic memory allocation failed.

The real allocatable memory required is N, and the complex allocatable memory required is $2 \times N$. Allocation failed before the solution could be computed.

See Section 3.7 in How to Use the NAG Library and its Documentation 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 $\kappa(A) = \|A^{-1}\|_1 \|A\|_1$, the condition number of A with respect to the solution of the linear equations. F04CJF 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

F04CJF 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 packed storage scheme is illustrated by the following example when $n = 4$ and UPLO = 'U'. Two-dimensional storage of the Hermitian matrix A :

$$\begin{array}{cccc} a_{11} & a_{12} & a_{13} & a_{14} \\ & a_{22} & a_{23} & a_{24} \\ & & a_{33} & a_{34} \\ & & & a_{44} \end{array} \quad (a_{ij} = \bar{a}_{ji}).$$

Packed storage of the upper triangle of A :

$$AP = [a_{11}, a_{12}, a_{22}, a_{13}, a_{23}, a_{33}, a_{14}, a_{24}, a_{34}, a_{44}].$$

The total number of floating-point operations required to solve the equations $AX = B$ is proportional to $(\frac{1}{3}n^3 + 2n^2r)$. 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.

Routine F04DJF is for complex symmetric matrices, and the real analogue of F04CJF is F04BJF.

10 Example

This example solves the equations

$$AX = B,$$

where A is the Hermitian indefinite matrix

$$A = \begin{pmatrix} -1.84 & 0.11 - 0.11i & -1.78 - 1.18i & 3.91 - 1.50i \\ 0.11 + 0.11i & -4.63 & -1.84 + 0.03i & 2.21 + 0.21i \\ -1.78 + 1.18i & -1.84 - 0.03i & -8.87 & 1.58 - 0.90i \\ 3.91 + 1.50i & 2.21 - 0.21i & 1.58 + 0.90i & -1.36 \end{pmatrix}$$

and

$$B = \begin{pmatrix} 2.98 - 10.18i & 28.68 - 39.89i \\ -9.58 + 3.88i & -24.79 - 8.40i \\ -0.77 - 16.05i & 4.23 - 70.02i \\ 7.79 + 5.48i & -35.39 + 18.01i \end{pmatrix}.$$

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 f04cjfe

```
!      F04CJF Example Program Text

!      Mark 26 Release. NAG Copyright 2016.

!      .. Use Statements ..
Use nag_library, Only: f04cjf, nag_wp, x04dbf, x04ddf
!      .. Implicit None Statement ..
Implicit None
!      .. Parameters ..
Integer, Parameter          :: nin = 5, nout = 6
Character (1), Parameter    :: uplo = 'U'
!      .. Local Scalars ..
Real (Kind=nag_wp)          :: errbnd, rcond
Integer                      :: i, ierr, ifail, j, ldb, n, nrhs
!      .. Local Arrays ..
Complex (Kind=nag_wp), Allocatable :: ap(:), b(:, :)
Integer, Allocatable          :: ipiv(:)
Character (1)                  :: clabs(1), rlabs(1)
!      .. Executable Statements ..
Write (nout,*) 'F04CJF Example Program Results'
Write (nout,*)
Flush (nout)
!      Skip heading in data file
Read (nin,*)
Read (nin,*) n, nrhs
ldb = n
Allocate (ap((n*(n+1))/2), b(ldb, nrhs), ipiv(n))
!      Read the upper or lower triangular part of the matrix A from
!      data file
If (uplo=='U') Then
    Read (nin,*)((ap(i+(j*(j-1))/2), j=i, n), i=1, n)
Else If (uplo=='L') Then
    Read (nin,*)((ap(i+((2*n-j)*(j-1))/2), j=1, i), i=1, n)
End If

!      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 f04cjf(uplo, n, nrhs, ap, ipiv, b, ldb, rcond, errbnd, ifail)

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

    ierr = 0
    Call x04dbf('General', ' ', n, nrhs, b, ldb, 'Bracketed', ' ', 'Solution', &
        'Integer', rlabs, 'Integer', clabs, 80, 0, 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 x04dbf('General',' ',n,nrhs,b,ldb,'Bracketed',' ','Solution',      &
        'Integer',rlabs,'Integer',clabs,80,0,ierr)

      Else If (ifail>0 .And. ifail<=n) Then
!       The upper triangular matrix U is exactly singular. Print
!       details of factorization
      Write (nout,*)
      Flush (nout)

      ierr = 0
      Call x04ddf(uplo,'Non-unit diagonal',n,ap,'Bracketed',' ',      &
        'Details of factorization','Integer',rlabs,'Integer',clabs,80,0,      &
        ierr)

!       Print pivot indices
      Write (nout,*)
      Write (nout,*) 'Pivot indices'
      Write (nout,99998) ipiv(1:n)
      Else
        Write (nout,99997) ifail
      End If

99999 Format (8X,1P,E9.1)
99998 Format ((1X,7I11))
99997 Format (1X,' ** F04CJF returned with IFAIL = ',I5)
      End Program f04cjfe

```

10.2 Program Data

F04CJF Example Program Data

```

      4              2                      : n, nrhs

( -1.84,  0.00) (  0.11, -0.11) ( -1.78, -1.18) (  3.91, -1.50)
              ( -4.63 , 0.00) ( -1.84,  0.03) (  2.21,  0.21)
              ( -8.87,  0.00) (  1.58, -0.90)
                      ( -1.36 , 0.00) : matrix A

(  2.98,-10.18) ( 28.68,-39.89)
( -9.58,  3.88) (-24.79, -8.40)
( -0.77,-16.05) (  4.23,-70.02)
(  7.79,  5.48) (-35.39, 18.01)          : matrix B

```

10.3 Program Results

F04CJF Example Program Results

```

Solution
              1              2
1 (  2.0000,  1.0000) ( -8.0000,  6.0000)
2 (  3.0000, -2.0000) (  7.0000, -2.0000)
3 ( -1.0000,  2.0000) ( -1.0000,  5.0000)
4 (  1.0000, -1.0000) (  3.0000, -4.0000)

```

Estimate of condition number
6.7E+00

Estimate of error bound for computed solutions
7.4E-16
