

NAG Library Routine Document

F07MBF (DSYSVX)

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

F07MBF (DSYSVX) uses the diagonal pivoting factorization to compute the solution to a real system of linear equations

$$AX = B,$$

where A is an n by n symmetric matrix and X and B are n by r matrices. Error bounds on the solution and a condition estimate are also provided.

2 Specification

```

SUBROUTINE F07MBF(FACT, UPLO, N, NRHS, A, LDA, AF, LDAF, IPIV, B, LDB,
1              X, LDX, RCOND, FERR, BERR, WORK, LWORK, IWORK, INFO)
    INTEGER      N, NRHS, LDA, LDAF, IPIV(*), LDB, LDX, LWORK,
1              IWORK(*), INFO
    double precision A(LDA,*), AF(LDAF,*), B(LDB,*), X(LDX,*), RCOND,
1              FERR(*), BERR(*), WORK(max(1,LWORK))
    CHARACTER*1  FACT, UPLO

```

The routine may be called by its LAPACK name ***dsysvx***.

3 Description

F07MBF (DSYSVX) performs the following steps:

1. If FACT = 'N', the diagonal pivoting method is used to factor A . The form of the factorization is $A = UDU^T$ if UPLO = 'U' or $A = LDL^T$ if UPLO = 'L', where U (or L) is a product of permutation and unit upper (lower) triangular matrices, and D is symmetric and block diagonal with 1 by 1 and 2 by 2 diagonal blocks.
2. If some $d_{ii} = 0$, so that D is exactly singular, then the routine returns with INFO = i . Otherwise, the factored form of A is used to estimate the condition number of the matrix A . If the reciprocal of the condition number is less than ***machine precision***, INFO = $N + 1$ is returned as a warning, but the routine still goes on to solve for X and compute error bounds as described below.
3. The system of equations is solved for X using the factored form of A .
4. Iterative refinement is applied to improve the computed solution matrix and to calculate error bounds and backward error estimates for it.

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>

Golub G H and Van Loan C F (1996) *Matrix Computations* (3rd Edition) Johns Hopkins University Press, Baltimore

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

5 Parameters

- 1: FACT – CHARACTER*1 *Input*
On entry: specifies whether or not the factorized form of the matrix A has been supplied.
FACT = 'F'
AF and IPIV contain the factorized form of the matrix A . AF and IPIV will not be modified.
FACT = 'N'
The matrix A will be copied to AF and factorized.
Constraint: FACT = 'F' or 'N'.

- 2: UPLO – CHARACTER*1 *Input*
On entry: if UPLO = 'U', the upper triangle of A is stored.
If UPLO = 'L', the lower triangle of A is stored.
Constraint: UPLO = 'U' or 'L'.

- 3: N – INTEGER *Input*
On entry: n , the number of linear equations, i.e., the order of the matrix A .
Constraint: $N \geq 0$.

- 4: NRHS – INTEGER *Input*
On entry: r , the number of right-hand sides, i.e., the number of columns of the matrix B .
Constraint: NRHS ≥ 0 .

- 5: A(LDA,*) – **double precision** array *Input*
Note: the second dimension of the array A must be at least $\max(1, N)$.
On entry: the n by n symmetric matrix A .
If UPLO = 'U', the upper triangular part of A must be stored and the elements of the array below the diagonal are not referenced.
If UPLO = 'L', the lower triangular part of A must be stored and the elements of the array above the diagonal are not referenced.

- 6: LDA – INTEGER *Input*
On entry: the first dimension of the array A as declared in the (sub)program from which F07MBF (DSYSVX) is called.
Constraint: LDA $\geq \max(1, N)$.

- 7: A(LDAF,*) – **double precision** array *Input/Output*
Note: the second dimension of the array AF must be at least $\max(1, N)$.
On entry: if FACT = 'F', AF contains the block diagonal matrix D and the multipliers used to obtain the factor U or L from the factorization $A = UDU^T$ or $A = LDL^T$ as computed by F07MDF (DSYTRF).
On exit: if FACT = 'N', AF returns the block diagonal matrix D and the multipliers used to obtain the factor U or L from the factorization $A = UDU^T$ or $A = LDL^T$.

- 8: LDAF – INTEGER *Input*
On entry: the first dimension of the array AF as declared in the (sub)program from which F07MBF (DSYSVX) is called.
Constraint: LDAF $\geq \max(1, N)$.

- 9: IPIV(*) – INTEGER array Input/Output
Note: the dimension of the array IPIV must be at least $\max(1, N)$.
On entry: if FACT = 'F', IPIV contains details of the interchanges and the block structure of D , as determined by F07MDF (DSYTRF).
 $IPIV(k) > 0$
 Rows and columns k and $IPIV(k)$ were interchanged and $D(k, k)$ is a 1 by 1 diagonal block.
 $UPLO = 'U'$ and $IPIV(k) = IPIV(k - 1) < 0$
 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.
 $UPLO = 'L'$ and $IPIV(k) = IPIV(k + 1) < 0$
 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.
On exit: if FACT = 'N', IPIV contains details of the interchanges and the block structure of D , as determined by F07MDF (DSYTRF).
- 10: B(LDB,*) – **double precision** array Input
Note: the second dimension of the array B must be at least $\max(1, NRHS)$.
On entry: the n by r right-hand side matrix B .
- 11: LDB – INTEGER Input
On entry: the first dimension of the array B as declared in the (sub)program from which F07MBF (DSYSVX) is called.
Constraint: $LDB \geq \max(1, N)$.
- 12: X(LDX,*) – **double precision** array Output
Note: the second dimension of the array X must be at least $\max(1, NRHS)$.
On exit: if INFO = 0 or $N + 1$, the n by r solution matrix X .
- 13: LDX – INTEGER Input
On entry: the first dimension of the array X as declared in the (sub)program from which F07MBF (DSYSVX) is called.
Constraint: $LDX \geq \max(1, N)$.
- 14: RCOND – **double precision** Output
On exit: the estimate of the reciprocal condition number of the matrix A . If $RCOND = 0$, the matrix may be exactly singular. This condition is indicated by $INFO > 0$ and $INFO \leq N$. Otherwise, if RCOND is less than the **machine precision**, the matrix is singular to working precision. This condition is indicated by $INFO = N + 1$.
- 15: FERR(*) – **double precision** array Output
Note: the dimension of the array FERR must be at least $\max(1, NRHS)$.
On exit: if INFO = 0 or $INFO = N + 1$, an estimate of the forward error bound for each computed solution vector, such that $\|\hat{x}_j - x_j\|_\infty / \|x_j\|_\infty \leq FERR(j)$ where $\hat{x}_j$ is the j th column of the computed solution returned in the array X and x_j is the corresponding column of the exact solution X . The estimate is as reliable as the estimate for RCOND, and is almost always a slight overestimate of the true error.

- 16: BERR(*) – *double precision* array *Output*
Note: the dimension of the array BERR must be at least $\max(1, \text{NRHS})$.
On exit: if $\text{INFO} = 0$ or $\text{INFO} = N + 1$, an estimate of the component-wise relative backward error of each computed solution vector $\hat{x}_j$ (i.e., the smallest relative change in any element of A or B that makes $\hat{x}_j$ an exact solution).
- 17: WORK($\max(1, \text{LWORK})$) – *double precision* array *Workspace*
On exit: if $\text{INFO} = 0$, WORK(1) returns the optimal LWORK.
- 18: LWORK – INTEGER *Input*
On entry: the dimension of the array WORK as declared in the (sub)program from which F07MBF (DSYSVX) is called.
 $\text{LWORK} \geq \max(1, 3 \times N)$, and for best performance, when $\text{FACT} = 'N'$,
 $\text{LWORK} \geq \max(1, 3 \times N, N \times \text{nb})$, where nb is the optimal blocksize for F07MDF (DSYTRF).
 If $\text{LWORK} = -1$, a workspace query is assumed; the routine only calculates the optimal size of the WORK array, returns this value as the first entry of the WORK array, and no error message related to LWORK is issued.
- 19: IWORK(*) – INTEGER array *Workspace*
Note: the dimension of the array IWORK must be at least $\max(1, N)$.
- 20: INFO – INTEGER *Output*
On exit: $\text{INFO} = 0$ unless the routine detects an error (see Section 6).

6 Error Indicators and Warnings

Errors or warnings detected by the routine:

$\text{INFO} < 0$

If $\text{INFO} = -i$, the i th argument had an illegal value. An explanatory message is output, and execution of the program is terminated.

$\text{INFO} > 0$ and $\text{INFO} \leq N$

If $\text{INFO} \leq N$, $d(i, i)$ is exactly zero. The factorization has been completed, but the factor D is exactly singular, so the solution and error bounds could not be computed. $\text{RCOND} = 0$ is returned.

$\text{INFO} = N + 1$

D is nonsingular, but RCOND is less than *machine precision*, meaning that the matrix is singular to working precision. Nevertheless, the solution and error bounds are computed because there are a number of situations where the computed solution can be more accurate than the value of RCOND would suggest.

7 Accuracy

For each right-hand side vector b , the computed solution $\hat{x}$ is the exact solution of a perturbed system of equations $(A + E)\hat{x} = b$, where

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

where ϵ is the *machine precision*. See Chapter 11 of Higham (2002) for further details.

If $\hat{x}$ is the true solution, then the computed solution x satisfies a forward error bound of the form

$$\frac{\|x - \hat{x}\|_{\infty}}{\|\hat{x}\|_{\infty}} \leq w_c \text{cond}(A, \hat{x}, b)$$

where $\text{cond}(A, \hat{x}, b) = \| |A| |\hat{x}| + |b| \|_{\infty} / \|\hat{x}\|_{\infty} \leq \text{cond}(A) = \| |A^{-1}| |A| \|_{\infty} \leq \kappa_{\infty}(A)$. If $\hat{x}$ is the j th column of X , then w_c is returned in `BERR(j)` and a bound on $\|x - \hat{x}\|_{\infty} / \|\hat{x}\|_{\infty}$ is returned in `FERR(j)`. See Section 4.4 of Anderson *et al.* (1999) for further details.

8 Further Comments

The factorization of A requires approximately $\frac{1}{3}n^3$ floating-point operations.

For each right-hand side, computation of the backward error involves a minimum of $4n^2$ floating-point operations. Each step of iterative refinement involves an additional $6n^2$ operations. At most five steps of iterative refinement are performed, but usually only one or two steps are required. Estimating the forward error involves solving a number of systems of equations of the form $Ax = b$; the number is usually 4 or 5 and never more than 11. Each solution involves approximately $2n^2$ operations.

The complex analogues of this routine are F07MPF (ZHESVX) for Hermitian matrices, and F07NPF (ZSYSVX) for symmetric matrices.

9 Example

This example solves the equations

$$AX = B,$$

where A is the symmetric matrix

$$A = \begin{pmatrix} -1.81 & 2.06 & 0.63 & -1.15 \\ 2.06 & 1.15 & 1.87 & 4.20 \\ 0.63 & 1.87 & -0.21 & 3.87 \\ -1.15 & 4.20 & 3.87 & 2.07 \end{pmatrix} \quad \text{and} \quad B = \begin{pmatrix} 0.96 & 3.93 \\ 6.07 & 19.25 \\ 8.38 & 9.90 \\ 9.50 & 27.85 \end{pmatrix}.$$

Error estimates for the solutions, and an estimate of the reciprocal of the condition number of the matrix A are also output.

9.1 Program Text

```
*      F07MBF Example Program Text
*      Mark 21 Release. NAG Copyright 2004.
*      .. Parameters ..
      INTEGER          NIN, NOUT
      PARAMETER        (NIN=5, NOUT=6)
      INTEGER          NB, NMAX, NRHSMX
      PARAMETER        (NB=64, NMAX=8, NRHSMX=2)
      INTEGER          LDA, LDAF, LDB, LDX, LWORK
      PARAMETER        (LDA=NMAX, LDAF=NMAX, LDB=NMAX, LDX=NMAX,
+                      LWORK=NB*NMAX)
*      .. Local Scalars ..
      DOUBLE PRECISION RCOND
      INTEGER          I, IFAIL, INFO, J, N, NRHS
*      .. Local Arrays ..
      DOUBLE PRECISION A(LDA,NMAX), AF(LDAF,NMAX), B(LDB,NRHSMX),
+                      BERR(NRHSMX), FERR(NRHSMX), WORK(LWORK),
+                      X(LDX,NRHSMX)
      INTEGER          IPIV(NMAX), IWORK(NMAX)
*      .. External Subroutines ..
      EXTERNAL         DSYSVX, X04CAF
*      .. Executable Statements ..
      WRITE (NOUT,*) 'F07MBF Example Program Results'
      WRITE (NOUT,*)
*      Skip heading in data file
      READ (NIN,*)
```

```

      READ (NIN,*) N, NRHS
      IF (N.LE.NMAX .AND. NRHS.LE.NRHSMX) THEN
*
*       Read the upper triangular part of A from data file
*
      READ (NIN,*) ((A(I,J),J=I,N),I=1,N)
*
*       Read B from data file
*
      READ (NIN,*) ((B(I,J),J=1,NRHS),I=1,N)
*
*       Solve the equations AX = B for X
*
      CALL DSYSVX('Not factored','Upper',N,NRHS,A,LDA,AF,LDAF,IPIV,B,
+             LDB,X,LDX,RCOND,FERR,BERR,WORK,LWORK,IWORK,INFO)
*
      IF ((INFO.EQ.0) .OR. (INFO.EQ.N+1)) THEN
*
*       Print solution, error bounds and condition number
*
      IFAIL = 0
      CALL X04CAF('General',' ',N,NRHS,X,LDX,'Solution(s)',IFAIL)
*
      WRITE (NOUT,*)
      WRITE (NOUT,*) 'Backward errors (machine-dependent)'
      WRITE (NOUT,99999) (BERR(J),J=1,NRHS)
      WRITE (NOUT,*)
      WRITE (NOUT,*)
+      'Estimated forward error bounds (machine-dependent)'
      WRITE (NOUT,99999) (FERR(J),J=1,NRHS)
      WRITE (NOUT,*)
      WRITE (NOUT,*) 'Estimate of reciprocal condition number'
      WRITE (NOUT,99999) RCOND
      WRITE (NOUT,*)
*
      IF (INFO.EQ.N+1) THEN
        WRITE (NOUT,*)
        WRITE (NOUT,*)
+        'The matrix A is singular to working precision'
      END IF
      ELSE
      WRITE (NOUT,99998) 'The diagonal block ', INFO,
+      ' of D is zero'
      END IF
      ELSE
      WRITE (NOUT,*) 'NMAX and/or NRHSMX too small'
      END IF
*
99999 FORMAT ((3X,1P,7E11.1))
99998 FORMAT (1X,A,I3,A)
      END

```

9.2 Program Data

F07MBF Example Program Data

```

      4      2      :Values of N and NRHS
-1.81    2.06    0.63  -1.15
        1.15    1.87    4.20
           -0.21    3.87
                2.07 :End of matrix A

0.96    3.93
6.07   19.25
8.38    9.90
9.50   27.85      :End of matrix B

```

9.3 Program Results

F07MBF Example Program Results

Solution(s)

	1	2
1	-5.0000	2.0000
2	-2.0000	3.0000
3	1.0000	4.0000
4	4.0000	1.0000

Backward errors (machine-dependent)

1.4E-16	1.0E-16
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Estimated forward error bounds (machine-dependent)

2.5E-14	3.2E-14
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Estimate of reciprocal condition number

1.3E-02
