

# NAG Library Routine Document

## F08MSF (ZBDSQR)

**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.

**Warning.** The specification of the parameter WORK changed at Mark 20: the length of WORK needs to be increased.

### 1 Purpose

F08MSF (ZBDSQR) computes the singular value decomposition of a complex general matrix which has been reduced to bidiagonal form.

### 2 Specification

SUBROUTINE F08MSF (UPLO, N, NCVT, NRU, NCC, D, E, VT, LDVT, U, LDU, C, &  
LDC, WORK, INFO)

INTEGER N, NCVT, NRU, NCC, LDVT, LDU, LDC, INFO  
REAL (KIND=nag\_wp) D(\*), E(\*), WORK(\*)  
COMPLEX (KIND=nag\_wp) VT(LDVT,\*), U(LDU,\*), C(LDC,\*)  
CHARACTER(1) UPLO

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

### 3 Description

F08MSF (ZBDSQR) computes the singular values and, optionally, the left or right singular vectors of a real upper or lower bidiagonal matrix  $B$ . In other words, it can compute the singular value decomposition (SVD) of  $B$  as

$$B = U \Sigma V^T.$$

Here  $\Sigma$  is a diagonal matrix with real diagonal elements  $\sigma_i$  (the singular values of  $B$ ), such that

$$\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_n \geq 0;$$

$U$  is an orthogonal matrix whose columns are the left singular vectors  $u_i$ ;  $V$  is an orthogonal matrix whose rows are the right singular vectors  $v_i$ . Thus

$$Bu_i = \sigma_i v_i \quad \text{and} \quad B^T v_i = \sigma_i u_i, \quad i = 1, 2, \dots, n.$$

To compute  $U$  and/or  $V^T$ , the arrays U and/or VT must be initialized to the unit matrix before F08MSF (ZBDSQR) is called.

The routine stores the real orthogonal matrices  $U$  and  $V^T$  in complex arrays U and VT, so that it may also be used to compute the SVD of a complex general matrix  $A$  which has been reduced to bidiagonal form by a unitary transformation:  $A = QBP^H$ . If  $A$  is  $m$  by  $n$  with  $m \geq n$ , then  $Q$  is  $m$  by  $n$  and  $P^H$  is  $n$  by  $n$ ; if  $A$  is  $n$  by  $p$  with  $n < p$ , then  $Q$  is  $n$  by  $n$  and  $P^H$  is  $n$  by  $p$ . In this case, the matrices  $Q$  and/or  $P^H$  must be formed explicitly by F08KTF (ZUNGBR) and passed to F08MSF (ZBDSQR) in the arrays U and/or VT respectively.

F08MSF (ZBDSQR) also has the capability of forming  $U^H C$ , where  $C$  is an arbitrary complex matrix; this is needed when using the SVD to solve linear least squares problems.

F08MSF (ZBDSQR) uses two different algorithms. If any singular vectors are required (i.e., if  $NCVT > 0$  or  $NRU > 0$  or  $NCC > 0$ ), the bidiagonal  $QR$  algorithm is used, switching between zero-shift and implicitly shifted forms to preserve the accuracy of small singular values, and switching between  $QR$  and  $QL$  variants in order to handle graded matrices effectively (see Demmel and Kahan (1990)). If only singular values are required (i.e., if  $NCVT = NRU = NCC = 0$ ), they are computed by the differential qd algorithm (see Fernando and Parlett (1994)), which is faster and can achieve even greater accuracy.

The singular vectors are normalized so that  $\|u_i\| = \|v_i\| = 1$ , but are determined only to within a complex factor of absolute value 1.

## 4 References

Demmel J W and Kahan W (1990) Accurate singular values of bidiagonal matrices *SIAM J. Sci. Statist. Comput.* **11** 873–912

Fernando K V and Parlett B N (1994) Accurate singular values and differential qd algorithms *Numer. Math.* **67** 191–229

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

## 5 Parameters

- 1: UPLO – CHARACTER(1) *Input*  
*On entry:* indicates whether  $B$  is an upper or lower bidiagonal matrix.  
 UPLO = 'U'  
 $B$  is an upper bidiagonal matrix.  
 UPLO = 'L'  
 $B$  is a lower bidiagonal matrix.  
*Constraint:* UPLO = 'U' or 'L'.
- 2: N – INTEGER *Input*  
*On entry:*  $n$ , the order of the matrix  $B$ .  
*Constraint:*  $N \geq 0$ .
- 3: NCVT – INTEGER *Input*  
*On entry:*  $ncvt$ , the number of columns of the matrix  $V^H$  of right singular vectors. Set NCVT = 0 if no right singular vectors are required.  
*Constraint:*  $NCVT \geq 0$ .
- 4: NRU – INTEGER *Input*  
*On entry:*  $nru$ , the number of rows of the matrix  $U$  of left singular vectors. Set NRU = 0 if no left singular vectors are required.  
*Constraint:*  $NRU \geq 0$ .
- 5: NCC – INTEGER *Input*  
*On entry:*  $ncc$ , the number of columns of the matrix  $C$ . Set NCC = 0 if no matrix  $C$  is supplied.  
*Constraint:*  $NCC \geq 0$ .
- 6: D(\*) – REAL (KIND=nag\_wp) array *Input/Output*  
**Note:** the dimension of the array D must be at least  $\max(1, N)$ .  
*On entry:* the diagonal elements of the bidiagonal matrix  $B$ .  
*On exit:* the singular values in decreasing order of magnitude, unless INFO > 0 (in which case see Section 6).

- 7: E(\*) – REAL (KIND=nag\_wp) array *Input/Output*  
**Note:** the dimension of the array E must be at least  $\max(1, N - 1)$ .  
*On entry:* the off-diagonal elements of the bidiagonal matrix  $B$ .  
*On exit:* E is overwritten, but if  $\text{INFO} > 0$  see Section 6.
- 8: VT(LDVT,\*) – COMPLEX (KIND=nag\_wp) array *Input/Output*  
**Note:** the second dimension of the array VT must be at least  $\max(1, \text{NCVT})$ .  
*On entry:* if  $\text{NCVT} > 0$ , VT must contain an  $n$  by  $\text{ncvt}$  matrix. If the right singular vectors of  $B$  are required,  $\text{ncvt} = n$  and VT must contain the unit matrix; if the right singular vectors of  $A$  are required, VT must contain the unitary matrix  $P^H$  returned by F08KTF (ZUNGBR) with  $\text{VECT} = 'P'$ .  
*On exit:* the  $n$  by  $\text{ncvt}$  matrix  $V^H$  or  $V^H$  of right singular vectors, stored by rows.  
 If  $\text{NCVT} = 0$ , VT is not referenced.
- 9: LDVT – INTEGER *Input*  
*On entry:* the first dimension of the array VT as declared in the (sub)program from which F08MSF (ZBDSQR) is called.  
*Constraints:*  
     if  $\text{NCVT} > 0$ ,  $\text{LDVT} \geq \max(1, N)$ ;  
     otherwise  $\text{LDVT} \geq 1$ .
- 10: U(LDU,\*) – COMPLEX (KIND=nag\_wp) array *Input/Output*  
**Note:** the second dimension of the array U must be at least  $\max(1, N)$ .  
*On entry:* if  $\text{NRU} > 0$ , U must contain an  $\text{nrU}$  by  $n$  matrix. If the left singular vectors of  $B$  are required,  $\text{nrU} = n$  and U must contain the unit matrix; if the left singular vectors of  $A$  are required, U must contain the unitary matrix  $Q$  returned by F08KTF (ZUNGBR) with  $\text{VECT} = 'Q'$ .  
*On exit:* the  $\text{nrU}$  by  $n$  matrix  $U$  or  $QU$  of left singular vectors, stored as columns of the matrix.  
 If  $\text{NRU} = 0$ , U is not referenced.
- 11: LDU – INTEGER *Input*  
*On entry:* the first dimension of the array U as declared in the (sub)program from which F08MSF (ZBDSQR) is called.  
*Constraint:*  $\text{LDU} \geq \max(1, \text{NRU})$ .
- 12: C(LDC,\*) – COMPLEX (KIND=nag\_wp) array *Input/Output*  
**Note:** the second dimension of the array C must be at least  $\max(1, \text{NCC})$ .  
*On entry:* the  $n$  by  $\text{ncc}$  matrix  $C$  if  $\text{NCC} > 0$ .  
*On exit:* C is overwritten by the matrix  $U^H C$ . If  $\text{NCC} = 0$ , C is not referenced.
- 13: LDC – INTEGER *Input*  
*On entry:* the first dimension of the array C as declared in the (sub)program from which F08MSF (ZBDSQR) is called.  
*Constraints:*  
     if  $\text{NCC} > 0$ ,  $\text{LDC} \geq \max(1, N)$ ;  
     otherwise  $\text{LDC} \geq 1$ .

- 14: WORK(\*) – REAL (KIND=nag\_wp) array *Workspace*  
**Note:** the dimension of the array WORK must be at least  $\max(1, 2 \times N)$  if  $\text{NCVT} = 0$  and  $\text{NRU} = 0$  and  $\text{NCC} = 0$ , and at least  $\max(1, 4 \times N)$  otherwise.
- 15: INFO – INTEGER *Output*  
*On exit:* INFO = 0 unless the routine detects an error (see Section 6).

## 6 Error Indicators and Warnings

INFO < 0

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

INFO > 0

The algorithm failed to converge and INFO specifies how many off-diagonals did not converge. In this case, D and E contain on exit the diagonal and off-diagonal elements, respectively, of a bidiagonal matrix orthogonally equivalent to  $B$ .

## 7 Accuracy

Each singular value and singular vector is computed to high relative accuracy. However, the reduction to bidiagonal form (prior to calling the routine) may exclude the possibility of obtaining high relative accuracy in the small singular values of the original matrix if its singular values vary widely in magnitude.

If  $\sigma_i$  is an exact singular value of  $B$  and  $\tilde{\sigma}_i$  is the corresponding computed value, then

$$|\tilde{\sigma}_i - \sigma_i| \leq p(m, n)\epsilon\sigma_i$$

where  $p(m, n)$  is a modestly increasing function of  $m$  and  $n$ , and  $\epsilon$  is the *machine precision*. If only singular values are computed, they are computed more accurately (i.e., the function  $p(m, n)$  is smaller), than when some singular vectors are also computed.

If  $u_i$  is an exact left singular vector of  $B$ , and  $\tilde{u}_i$  is the corresponding computed left singular vector, then the angle  $\theta(\tilde{u}_i, u_i)$  between them is bounded as follows:

$$\theta(\tilde{u}_i, u_i) \leq \frac{p(m, n)\epsilon}{\text{relgap}_i}$$

where  $\text{relgap}_i$  is the relative gap between  $\sigma_i$  and the other singular values, defined by

$$\text{relgap}_i = \min_{i \neq j} \frac{|\sigma_i - \sigma_j|}{(\sigma_i + \sigma_j)}$$

A similar error bound holds for the right singular vectors.

## 8 Parallelism and Performance

F08MSF (ZBDSQR) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

F08MSF (ZBDSQR) 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 total number of real floating-point operations is roughly proportional to  $n^2$  if only the singular values are computed. About  $12n^2 \times nru$  additional operations are required to compute the left singular vectors and about  $12n^2 \times ncv$  to compute the right singular vectors. The operations to compute the singular values must all be performed in scalar mode; the additional operations to compute the singular vectors can be vectorized and on some machines may be performed much faster.

The real analogue of this routine is F08MEF (DBDSQR).

## 10 Example

See Section 10 in F08KTF (ZUNGBR), which illustrates the use of the routine to compute the singular value decomposition of a general matrix.

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