

## NAG Toolbox

### nag\_lapack\_dpqr (f08jg)

#### 1 Purpose

nag\_lapack\_dpqr (f08jg) computes all the eigenvalues and, optionally, all the eigenvectors of a real symmetric positive definite tridiagonal matrix, or of a real symmetric positive definite matrix which has been reduced to tridiagonal form.

#### 2 Syntax

```
[d, e, z, info] = nag_lapack_dpqr(compz, d, e, z, 'n', n)
```

```
[d, e, z, info] = f08jg(compz, d, e, z, 'n', n)
```

#### 3 Description

nag\_lapack\_dpqr (f08jg) computes all the eigenvalues and, optionally, all the eigenvectors of a real symmetric positive definite tridiagonal matrix  $T$ . In other words, it can compute the spectral factorization of  $T$  as

$$T = Z\Lambda Z^T,$$

where  $\Lambda$  is a diagonal matrix whose diagonal elements are the eigenvalues  $\lambda_i$ , and  $Z$  is the orthogonal matrix whose columns are the eigenvectors  $z_i$ . Thus

$$Tz_i = \lambda_i z_i, \quad i = 1, 2, \dots, n.$$

The function may also be used to compute all the eigenvalues and eigenvectors of a real symmetric positive definite matrix  $A$  which has been reduced to tridiagonal form  $T$ :

$$\begin{aligned} A &= QTQ^T, \text{ where } Q \text{ is orthogonal} \\ &= (QZ)\Lambda(QZ)^T. \end{aligned}$$

In this case, the matrix  $Q$  must be formed explicitly and passed to nag\_lapack\_dpqr (f08jg), which must be called with **compz** = 'V'. The functions which must be called to perform the reduction to tridiagonal form and form  $Q$  are:

full matrix	f08fe and f08ff
full matrix, packed storage	f08ge and f08gf
band matrix	f08he with <b>vect</b> = 'V'.

nag\_lapack\_dpqr (f08jg) first factorizes  $T$  as  $LDL^T$  where  $L$  is unit lower bidiagonal and  $D$  is diagonal. It forms the bidiagonal matrix  $B = LD^{\frac{1}{2}}$ , and then calls nag\_lapack\_dbdsqr (f08me) to compute the singular values of  $B$  which are the same as the eigenvalues of  $T$ . The method used by the function allows high relative accuracy to be achieved in the small eigenvalues of  $T$ . The eigenvectors are normalized so that  $\|z_i\|_2 = 1$ , but are determined only to within a factor  $\pm 1$ .

#### 4 References

Barlow J and Demmel J W (1990) Computing accurate eigensystems of scaled diagonally dominant matrices *SIAM J. Numer. Anal.* **27** 762–791

## 5 Parameters

### 5.1 Compulsory Input Parameters

1: **compz** – CHARACTER(1)

Indicates whether the eigenvectors are to be computed.

**compz** = 'N'

Only the eigenvalues are computed (and the array **z** is not referenced).

**compz** = 'V'

The eigenvalues and eigenvectors of  $A$  are computed (and the array **z** must contain the matrix  $Q$  on entry).

**compz** = 'I'

The eigenvalues and eigenvectors of  $T$  are computed (and the array **z** is initialized by the function).

*Constraint:* **compz** = 'N', 'V' or 'I'.

2: **d**(:) – REAL (KIND=nag\_wp) array

The dimension of the array **d** must be at least  $\max(1, \mathbf{n})$

The diagonal elements of the tridiagonal matrix  $T$ .

3: **e**(:) – REAL (KIND=nag\_wp) array

The dimension of the array **e** must be at least  $\max(1, \mathbf{n} - 1)$

The off-diagonal elements of the tridiagonal matrix  $T$ .

4: **z**(ldz,:) – REAL (KIND=nag\_wp) array

The first dimension,  $ldz$ , of the array **z** must satisfy

if **compz** = 'V' or 'I',  $ldz \geq \max(1, \mathbf{n})$ ;  
if **compz** = 'N',  $ldz \geq 1$ .

The second dimension of the array **z** must be at least  $\max(1, \mathbf{n})$  if **compz** = 'V' or 'I' and at least 1 if **compz** = 'N'.

If **compz** = 'V', **z** must contain the orthogonal matrix  $Q$  from the reduction to tridiagonal form.

If **compz** = 'I', **z** need not be set.

### 5.2 Optional Input Parameters

1: **n** – INTEGER

*Default:* the first dimension of the array **d** and the second dimension of the array **d**. (An error is raised if these dimensions are not equal.)

$n$ , the order of the matrix  $T$ .

*Constraint:*  $\mathbf{n} \geq 0$ .

### 5.3 Output Parameters

1: **d**(:) – REAL (KIND=nag\_wp) array

The dimension of the array **d** will be  $\max(1, \mathbf{n})$

The  $n$  eigenvalues in descending order, unless **info** > 0, in which case **d** is overwritten.

2: **e**(:) – REAL (KIND=nag\_wp) array

The dimension of the array **e** will be  $\max(1, \mathbf{n} - 1)$

3: **z**(ldz,:) – REAL (KIND=nag\_wp) array

The first dimension, *ldz*, of the array **z** will be

if **compz** = 'V' or 'I',  $ldz = \max(1, \mathbf{n})$ ;  
if **compz** = 'N',  $ldz = 1$ .

The second dimension of the array **z** will be  $\max(1, \mathbf{n})$  if **compz** = 'V' or 'I' and at least 1 if **compz** = 'N'.

If **compz** = 'V' or 'I', the *n* required orthonormal eigenvectors stored as columns of *Z*; the *i*th column corresponds to the *i*th eigenvalue, where  $i = 1, 2, \dots, n$ , unless **info** > 0.

If **compz** = 'N', **z** is not referenced.

4: **info** – INTEGER

**info** = 0 unless the function detects an error (see Section 6).

## 6 Error Indicators and Warnings

**info** =  $-i$

If **info** =  $-i$ , parameter *i* had an illegal value on entry. The parameters are numbered as follows:

1: **compz**, 2: **n**, 3: **d**, 4: **e**, 5: **z**, 6: **ldz**, 7: **work**, 8: **info**.

It is possible that **info** refers to a parameter that is omitted from the MATLAB interface. This usually indicates that an error in one of the other input parameters has caused an incorrect value to be inferred.

**info** > 0

If **info** = *i*, the leading minor of order *i* is not positive definite and the Cholesky factorization of *T* could not be completed. Hence *T* itself is not positive definite.

If **info** =  $\mathbf{n} + i$ , the algorithm to compute the singular values of the Cholesky factor *B* failed to converge; *i* off-diagonal elements did not converge to zero.

## 7 Accuracy

The eigenvalues and eigenvectors of *T* are computed to high relative accuracy which means that if they vary widely in magnitude, then any small eigenvalues (and corresponding eigenvectors) will be computed more accurately than, for example, with the standard *QR* method. However, the reduction to tridiagonal form (prior to calling the function) may exclude the possibility of obtaining high relative accuracy in the small eigenvalues of the original matrix if its eigenvalues vary widely in magnitude.

To be more precise, let *H* be the tridiagonal matrix defined by  $H = DTD$ , where *D* is diagonal with  $d_{ii} = t_{ii}^{-\frac{1}{2}}$ , and  $h_{ii} = 1$  for all *i*. If  $\lambda_i$  is an exact eigenvalue of *T* and  $\tilde{\lambda}_i$  is the corresponding computed value, then

$$|\tilde{\lambda}_i - \lambda_i| \leq c(n)\epsilon\kappa_2(H)\lambda_i$$

where  $c(n)$  is a modestly increasing function of *n*,  $\epsilon$  is the *machine precision*, and  $\kappa_2(H)$  is the condition number of *H* with respect to inversion defined by:  $\kappa_2(H) = \|H\| \cdot \|H^{-1}\|$ .

If  $z_i$  is the corresponding exact eigenvector of *T*, and  $\tilde{z}_i$  is the corresponding computed eigenvector, then the angle  $\theta(\tilde{z}_i, z_i)$  between them is bounded as follows:

$$\theta(\tilde{z}_i, z_i) \leq \frac{c(n)\epsilon\kappa_2(H)}{\text{relgap}_i}$$

where  $\text{relgap}_i$  is the relative gap between  $\lambda_i$  and the other eigenvalues, defined by

$$\text{relgap}_i = \min_{i \neq j} \frac{|\lambda_i - \lambda_j|}{(\lambda_i + \lambda_j)}.$$

## 8 Further Comments

The total number of floating-point operations is typically about  $30n^2$  if **compz** = 'N' and about  $6n^3$  if **compz** = 'V' or 'I', but depends on how rapidly the algorithm converges. When **compz** = 'N', the operations are all performed in scalar mode; the additional operations to compute the eigenvectors when **compz** = 'V' or 'I' can be vectorized and on some machines may be performed much faster.

The complex analogue of this function is `nag_lapack_zpteqr` (f08ju).

## 9 Example

This example computes all the eigenvalues and eigenvectors of the symmetric positive definite tridiagonal matrix  $T$ , where

$$T = \begin{pmatrix} 4.16 & 3.17 & 0.00 & 0.00 \\ 3.17 & 5.25 & -0.97 & 0.00 \\ 0.00 & -0.97 & 1.09 & 0.55 \\ 0.00 & 0.00 & 0.55 & 0.62 \end{pmatrix}.$$

### 9.1 Program Text

```
function f08jg_example
fprintf('f08jg example results\n\n');

% Symmetric tridiagonal A stored as diagonal and off-diagonal
n = 4;
d = [4.16;      5.25;      1.09;      0.62];
e = [3.17;      -0.97;      0.55];

% All eigenvalues and eigenvectors of A
compz = 'I';
z = zeros(4, 4);
[w, ~, z, info] = f08jg( ...
                    compz, d, e, z);

% Normalize eigenvectors: largest element positive
for j = 1:n
    [~,k] = max(abs(z(:,j)));
    if z(k,j) < 0;
        z(:,j) = -z(:,j);
    end
end

disp('Eigenvalues');
disp(w');
disp('Eigenvectors');
disp(z);
```

## 9.2 Program Results

f08jg example results

Eigenvalues

8.0023	1.9926	1.0014	0.1237
--------	--------	--------	--------

Eigenvectors

0.6326	0.6245	-0.4191	0.1847
0.7668	-0.4270	0.4176	-0.2352
-0.1082	0.6071	0.4594	-0.6393
-0.0081	0.2432	0.6625	0.7084

---