

# NAG Library Function Document

## nag\_sum\_fft\_qtrcosine (c06rhc)

### 1 Purpose

nag\_sum\_fft\_qtrcosine (c06rhc) computes the discrete quarter-wave Fourier cosine transforms of  $m$  sequences of real data values. The elements of each sequence and its transform are stored contiguously.

### 2 Specification

```
#include <nag.h>
#include <nagc06.h>

void nag_sum_fft_qtrcosine (Nag_TransformDirection direct, Integer m,
    Integer n, double x[], NagError *fail)
```

### 3 Description

Given  $m$  sequences of  $n$  real data values  $x_j^p$ , for  $j = 0, 1, \dots, n-1$  and  $p = 1, 2, \dots, m$ , nag\_sum\_fft\_qtrcosine (c06rhc) simultaneously calculates the quarter-wave Fourier cosine transforms of all the sequences defined by

$$\hat{x}_k^p = \frac{1}{\sqrt{n}} \left( \frac{1}{2} x_0^p + \sum_{j=1}^{n-1} x_j^p \times \cos \left( j(2k+1) \frac{\pi}{2n} \right) \right), \quad \text{if } \mathbf{direct} = \text{Nag\_ForwardTransform},$$

or its inverse

$$x_k^p = \frac{2}{\sqrt{n}} \sum_{j=0}^{n-1} \hat{x}_j^p \times \cos \left( (2j+1) k \frac{\pi}{2n} \right), \quad \text{if } \mathbf{direct} = \text{Nag\_BackwardTransform},$$

where  $k = 0, 1, \dots, n-1$  and  $p = 1, 2, \dots, m$ .

(Note the scale factor  $\frac{1}{\sqrt{n}}$  in this definition.)

A call of nag\_sum\_fft\_qtrcosine (c06rhc) with **direct** = Nag\_ForwardTransform followed by a call with **direct** = Nag\_BackwardTransform will restore the original data.

The two transforms are also known as type-III DCT and type-II DCT, respectively.

The transform calculated by this function can be used to solve Poisson's equation when the derivative of the solution is specified at the left boundary, and the solution is specified at the right boundary (see Swarztrauber (1977)).

The function uses a variant of the fast Fourier transform (FFT) algorithm (see Brigham (1974)) known as the Stockham self-sorting algorithm, described in Temperton (1983), together with pre- and post-processing stages described in Swarztrauber (1982). Special coding is provided for the factors 2, 3, 4 and 5.

### 4 References

Brigham E O (1974) *The Fast Fourier Transform* Prentice–Hall

Swarztrauber P N (1977) The methods of cyclic reduction, Fourier analysis and the FACR algorithm for the discrete solution of Poisson's equation on a rectangle *SIAM Rev.* **19**(3) 490–501

Swarztrauber P N (1982) Vectorizing the FFT's *Parallel Computation* (ed G Rodrigue) 51–83 Academic Press

Temperton C (1983) Fast mixed-radix real Fourier transforms *J. Comput. Phys.* **52** 340–350

## 5 Arguments

- 1: **direct** – Nag\_TransformDirection *Input*  
*On entry:* indicates the transform, as defined in Section 3, to be computed.  
**direct** = Nag\_ForwardTransform  
 Forward transform.  
**direct** = Nag\_BackwardTransform  
 Inverse transform.  
*Constraint:* **direct** = Nag\_ForwardTransform or Nag\_BackwardTransform.
- 2: **m** – Integer *Input*  
*On entry:*  $m$ , the number of sequences to be transformed.  
*Constraint:*  $m \geq 1$ .
- 3: **n** – Integer *Input*  
*On entry:*  $n$ , the number of real values in each sequence.  
*Constraint:*  $n \geq 1$ .
- 4: **x[n × m]** – double *Input/Output*  
*On entry:* the  $m$  data sequences to be transformed. The data values of the  $p$ th sequence to be transformed, denoted by  $x_j^p$ , for  $j = 0, 1, \dots, n - 1$  and  $p = 1, 2, \dots, m$ , must be stored in  $x[(p - 1) \times n + j]$ .  
*On exit:* the  $m$  quarter-wave cosine transforms, overwriting the corresponding original sequences. The  $n$  components of the  $p$ th quarter-wave cosine transform, denoted by  $\hat{x}_k^p$ , for  $k = 0, 1, \dots, n - 1$  and  $p = 1, 2, \dots, m$ , are stored in  $x[(p - 1) \times n + k]$ .
- 5: **fail** – NagError \* *Input/Output*  
 The NAG error argument (see Section 2.7 in How to Use the NAG Library and its Documentation).

## 6 Error Indicators and Warnings

### NE\_ALLOC\_FAIL

Dynamic memory allocation failed.

See Section 3.2.1.2 in How to Use the NAG Library and its Documentation for further information.

### NE\_BAD\_PARAM

On entry, argument  $\langle value \rangle$  had an illegal value.

### NE\_INT

On entry,  $m = \langle value \rangle$ .

Constraint:  $m \geq 1$ .

On entry,  $n = \langle value \rangle$ .

Constraint:  $n \geq 1$ .

### NE\_INTERNAL\_ERROR

An internal error has occurred in this function. Check the function call and any array sizes. If the call is correct then please contact NAG for assistance.

An unexpected error has been triggered by this function. Please contact NAG.  
See Section 3.6.6 in How to Use the NAG Library and its Documentation for further information.

## NE\_NO\_LICENCE

Your licence key may have expired or may not have been installed correctly.  
See Section 3.6.5 in How to Use the NAG Library and its Documentation for further information.

## 7 Accuracy

Some indication of accuracy can be obtained by performing a subsequent inverse transform and comparing the results with the original sequence (in exact arithmetic they would be identical).

## 8 Parallelism and Performance

`nag_sum_fft_qtrcosine` (c06rhc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

Please consult the x06 Chapter Introduction for information on how to control and interrogate the OpenMP environment used within this function. Please also consult the Users' Note for your implementation for any additional implementation-specific information.

## 9 Further Comments

The time taken by `nag_sum_fft_qtrcosine` (c06rhc) is approximately proportional to  $nm \log(n)$ , but also depends on the factors of  $n$ . `nag_sum_fft_qtrcosine` (c06rhc) is fastest if the only prime factors of  $n$  are 2, 3 and 5, and is particularly slow if  $n$  is a large prime, or has large prime factors. This function internally allocates a workspace of order  $O(n)$  double values.

## 10 Example

This example reads in sequences of real data values and prints their quarter-wave cosine transforms as computed by `nag_sum_fft_qtrcosine` (c06rhc) with `direct = Nag_ForwardTransform`. It then calls the function again with `direct = Nag_BackwardTransform` and prints the results which may be compared with the original data.

### 10.1 Program Text

```
/* nag_sum_fft_qtrcosine (c06rhc) Example Program.
 *
 * NAGPRODCODE Version.
 *
 * Copyright 2016 Numerical Algorithms Group.
 *
 * Mark 26, 2016.
 */

#include <nag.h>
#include <stdio.h>
#include <nag_stdlib.h>
#include <nagc06.h>

int main(void)
{
    /* Scalars */
    Integer exit_status = 0, j, m, n;
    /* Arrays */
    double *x = 0;
    char title[60];
    /* Nag Types */
    NagError fail;

    INIT_FAIL(fail);
```

```

printf("nag_sum_fft_qtrcosine (c06rhc) Example Program Results\n");
fflush(stdout);

/* Read dimensions of array from data file. */
#ifdef _WIN32
scanf_s("%*[\n] %" NAG_IFMT "%" NAG_IFMT "%*[\n]", &m, &n);
#else
scanf("%*[\n] %" NAG_IFMT "%" NAG_IFMT "%*[\n]", &m, &n);
#endif
if (!(x = NAG_ALLOC((m * n), double)))
{
printf("Allocation failure\n");
exit_status = -1;
goto END;
}

/* Read array values from data file and print out. */
for (j = 0; j < m * n; j++)
#ifdef _WIN32
scanf_s("%lf", &x[j]);
#else
scanf("%lf", &x[j]);
#endif
#ifdef _WIN32
sprintf_s(title, (unsigned)_countof(title), "\n Original data values\n");
#else
sprintf(title, "\n Original data values\n");
#endif
nag_gen_real_mat_print_comp(Nag_RowMajor, Nag_GeneralMatrix,
                           Nag_NonUnitDiag, m, n, x, n, "%9.4f",
                           title, Nag_NoLabels, 0, Nag_NoLabels,
                           0, 80, 0, NULL, &fail);
if (fail.code != NE_NOERROR) {
printf("Error from nag_gen_real_mat_print_comp (x04cbc).\n%s\n",
       fail.message);
exit_status = 1;
goto END;
}

/* nag_sum_fft_qtrcosine (c06rhc).
 * Discrete quarter-wave sine transforms
 */
nag_sum_fft_qtrcosine(Nag_ForwardTransform, m, n, x, &fail);
if (fail.code != NE_NOERROR) {
printf("Error from nag_sum_fft_qtrcosine (c06rhc).\n%s\n", fail.message);
exit_status = 2;
goto END;
}

#ifdef _WIN32
sprintf_s(title, (unsigned)_countof(title),
         "\n Discrete quarter-wave Fourier cosine transforms\n");
#else
sprintf(title, "\n Discrete quarter-wave Fourier cosine transforms\n");
#endif
nag_gen_real_mat_print_comp(Nag_RowMajor, Nag_GeneralMatrix,
                           Nag_NonUnitDiag, m, n, x, n, "%9.4f",
                           title, Nag_NoLabels, 0, Nag_NoLabels,
                           0, 80, 0, NULL, &fail);
if (fail.code != NE_NOERROR) {
printf("Error from nag_gen_real_mat_print_comp (x04cbc).\n%s\n",
       fail.message);
exit_status = 3;
goto END;
}

/* Call backward transform to restore the original data. */
nag_sum_fft_qtrcosine(Nag_BackwardTransform, m, n, x, &fail);
if (fail.code != NE_NOERROR) {
printf("Error from nag_sum_fft_qtrcosine (c06rhc).\n%s\n", fail.message);
}

```

```

        exit_status = 4;
        goto END;
    }

#ifdef _WIN32
    sprintf_s(title, (unsigned)_countof(title),
              "\n Original data as restored by inverse transform\n");
#else
    sprintf(title, "\n Original data as restored by inverse transform\n");
#endif
    nag_gen_real_mat_print_comp(Nag_RowMajor, Nag_GeneralMatrix,
                               Nag_NonUnitDiag, m, n, x, n, "%9.4f",
                               title, Nag_NoLabels, 0, Nag_NoLabels,
                               0, 80, 0, NULL, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_gen_real_mat_print_comp (x04cbc).\n%s\n",
              fail.message);
        exit_status = 5;
        goto END;
    }

END:
    NAG_FREE(x);
    return exit_status;
}

```

## 10.2 Program Data

nag\_sum\_fft\_qtrcosine (c06rhc) Example Program Data

```

3          6                               : m, n

0.3854  0.6772  0.1138  0.6751  0.6362  0.1424
0.5417  0.2983  0.1181  0.7255  0.8638  0.8723
0.9172  0.0644  0.6037  0.6430  0.0428  0.4815 : x

```

## 10.3 Program Results

nag\_sum\_fft\_qtrcosine (c06rhc) Example Program Results

Original data values

```

0.3854  0.6772  0.1138  0.6751  0.6362  0.1424
0.5417  0.2983  0.1181  0.7255  0.8638  0.8723
0.9172  0.0644  0.6037  0.6430  0.0428  0.4815

```

Discrete quarter-wave Fourier cosine transforms

```

0.7257  -0.2216  0.1011  0.2355  -0.1406  -0.2282
0.7479  -0.6172  0.4112  0.0791  0.1331  -0.0906
0.6713  -0.1363  -0.0064  -0.0285  0.4758  0.1475

```

Original data as restored by inverse transform

```

0.3854  0.6772  0.1138  0.6751  0.6362  0.1424
0.5417  0.2983  0.1181  0.7255  0.8638  0.8723
0.9172  0.0644  0.6037  0.6430  0.0428  0.4815

```

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