

## NAG Library Function Document

### nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc)

#### 1 Purpose

nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) solves a general two-point boundary value problem for a nonlinear mixed order system of ordinary differential equations.

#### 2 Specification

```
#include <nag.h>
#include <nagd02.h>

void nag_ode_bvp_coll_nlin_solve (
    void (*ffun)(double x, const double y[], Integer neq, const Integer m[],
                double f[], Nag_Comm *comm),
    void (*fjac)(double x, const double y[], Integer neq, const Integer m[],
                double dfdy[], Nag_Comm *comm),
    void (*gafun)(const double ya[], Integer neq, const Integer m[],
                 Integer nlbc, double ga[], Nag_Comm *comm),
    void (*gbfun)(const double yb[], Integer neq, const Integer m[],
                 Integer nrbc, double gb[], Nag_Comm *comm),
    void (*gajac)(const double ya[], Integer neq, const Integer m[],
                 Integer nlbc, double dgady[], Nag_Comm *comm),
    void (*gbjac)(const double yb[], Integer neq, const Integer m[],
                 Integer nrbc, double dgbdy[], Nag_Comm *comm),
    void (*guess)(double x, Integer neq, const Integer m[], double y[],
                 double dym[], Nag_Comm *comm),
    double rcomm[], Integer icomm[], Nag_Comm *comm, NagError *fail)
```

#### 3 Description

nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) and its associated functions (nag\_ode\_bvp\_coll\_nlin\_setup (d02tvc), nag\_ode\_bvp\_coll\_nlin\_contin (d02txc), nag\_ode\_bvp\_coll\_nlin\_interp (d02tyc) and nag\_ode\_bvp\_coll\_nlin\_diag (d02tzc)) solve the two-point boundary value problem for a nonlinear mixed order system of ordinary differential equations

$$\left. \begin{aligned} y_1^{(m_1)}(x) &= f_1\left(x, y_1, y_1^{(1)}, \dots, y_1^{(m_1-1)}, y_2, \dots, y_n^{(m_n-1)}\right) \\ y_2^{(m_2)}(x) &= f_2\left(x, y_1, y_1^{(1)}, \dots, y_1^{(m_1-1)}, y_2, \dots, y_n^{(m_n-1)}\right) \\ &\vdots \\ y_n^{(m_n)}(x) &= f_n\left(x, y_1, y_1^{(1)}, \dots, y_1^{(m_1-1)}, y_2, \dots, y_n^{(m_n-1)}\right) \end{aligned} \right\}$$

over an interval  $[a, b]$  subject to  $p (> 0)$  nonlinear boundary conditions at  $a$  and  $q (> 0)$  nonlinear boundary conditions at  $b$ , where  $p + q = \sum_{i=1}^n m_i$ . Note that  $y_i^{(m)}(x)$  is the  $m$ th derivative of the  $i$ th solution component. Hence  $y_i^{(0)}(x) = y_i(x)$ . The left boundary conditions at  $a$  are defined as

$$g_i(z(y(a))) = 0, \quad i = 1, 2, \dots, p,$$

and the right boundary conditions at  $b$  as

$$\bar{g}_j(z(y(b))) = 0, \quad j = 1, 2, \dots, q,$$

where  $y = (y_1, y_2, \dots, y_n)$  and

$$z(y(x)) = \left( y_1(x), y_1^{(1)}(x), \dots, y_1^{(m_1-1)}(x), y_2(x), \dots, y_n^{(m_n-1)}(x) \right).$$

First, `nag_ode_bvp_coll_nlin_setup` (d02tvc) must be called to specify the initial mesh, error requirements and other details. Note that the error requirements apply only to the solution components  $y_1, y_2, \dots, y_n$  and that no error control is applied to derivatives of solution components. (If error control is required on derivatives then the system must be reduced in order by introducing the derivatives whose error is to be controlled as new variables. See Section 9 in `nag_ode_bvp_coll_nlin_setup` (d02tvc).) Then, `nag_ode_bvp_coll_nlin_solve` (d02tlc) can be used to solve the boundary value problem. After successful computation, `nag_ode_bvp_coll_nlin_diag` (d02tzc) can be used to ascertain details about the final mesh and other details of the solution procedure, and `nag_ode_bvp_coll_nlin_interp` (d02tyc) can be used to compute the approximate solution anywhere on the interval  $[a, b]$ .

A description of the numerical technique used in `nag_ode_bvp_coll_nlin_solve` (d02tlc) is given in Section 3 in `nag_ode_bvp_coll_nlin_setup` (d02tvc).

`nag_ode_bvp_coll_nlin_solve` (d02tlc) can also be used in the solution of a series of problems, for example in performing continuation, when the mesh used to compute the solution of one problem is to be used as the initial mesh for the solution of the next related problem. `nag_ode_bvp_coll_nlin_contin` (d02txc) should be used in between calls to `nag_ode_bvp_coll_nlin_solve` (d02tlc) in this context.

See Section 9 in `nag_ode_bvp_coll_nlin_setup` (d02tvc) for details of how to solve boundary value problems of a more general nature.

The functions are based on modified versions of the codes COLSYS and COLNEW (see Ascher *et al.* (1979) and Ascher and Bader (1987)). A comprehensive treatment of the numerical solution of boundary value problems can be found in Ascher *et al.* (1988) and Keller (1992).

## 4 References

Ascher U M and Bader G (1987) A new basis implementation for a mixed order boundary value ODE solver *SIAM J. Sci. Stat. Comput.* **8** 483–500

Ascher U M, Christiansen J and Russell R D (1979) A collocation solver for mixed order systems of boundary value problems *Math. Comput.* **33** 659–679

Ascher U M, Mattheij R M M and Russell R D (1988) *Numerical Solution of Boundary Value Problems for Ordinary Differential Equations* Prentice–Hall

Keller H B (1992) *Numerical Methods for Two-point Boundary-value Problems* Dover, New York

## 5 Arguments

- 1: **ffun** – function, supplied by the user *External Function*  
**ffun** must evaluate the functions  $f_i$  for given values  $x, z(y(x))$ .

The specification of **ffun** is:

```
void ffun (double x, const double y[], Integer neq, const Integer m[],
          double f[], Nag_Comm *comm)
```

1: **x** – double *Input*

*On entry:*  $x$ , the independent variable.

2: **y**[*dim*] – const double *Input*

**Note:** the dimension, *dim*, of the array **y** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where  $\mathbf{Y}(i, j)$  appears in this document, it refers to the array element  $\mathbf{y}[j \times \mathbf{neq} + i - 1]$ .

*On entry:*  $\mathbf{Y}(i, j)$  contains  $y_i^{(j)}(x)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(x) = y_i(x)$ .

3: **neq** – Integer *Input*

*On entry:* the number of differential equations.

4: **m[neq]** – const Integer *Input*

*On entry:* **m**[ $i - 1$ ] contains  $m_i$ , the order of the  $i$ th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

5: **f[neq]** – double *Output*

*On exit:* **f**[ $i - 1$ ] must contain  $f_i$ , for  $i = 1, 2, \dots, \mathbf{neq}$ .

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **ffun**.

**user** – double \*

**iuser** – Integer \*

**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **ffun** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

2: **fjac** – function, supplied by the user *External Function*

**fjac** must evaluate the partial derivatives of  $f_i$  with respect to the elements of

$$z(y(x)) = \left( y_1(x), y_1^1(x), \dots, y_1^{(m_1-1)}(x), y_2(x), \dots, y_n^{(m_n-1)}(x) \right).$$

The specification of **fjac** is:

```
void fjac (double x, const double y[], Integer neq, const Integer m[],
          double dfdy[], Nag_Comm *comm)
```

1: **x** – double *Input*

*On entry:*  $x$ , the independent variable.

2: **y[dim]** – const double *Input*

**Note:** the dimension,  $dim$ , of the array **y** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where  $\mathbf{Y}(i, j)$  appears in this document, it refers to the array element **y**[ $j \times \mathbf{neq} + i - 1$ ].

*On entry:*  $\mathbf{Y}(i, j)$  contains  $y_i^{(j)}(x)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(x) = y_i(x)$ .

3: **neq** – Integer *Input*

*On entry:* the number of differential equations.

4: **m[neq]** – const Integer *Input*

*On entry:* **m**[ $i - 1$ ] contains  $m_i$ , the order of the  $i$ th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

5: **dfdy**[*dim*] – double *Input/Output*

**Note:** the dimension, *dim*, of the array **dfdy** is  $\mathbf{neq} \times \mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **DFDY**(*i, j, k*) appears in this document, it refers to the array element **dfdy**[ $k \times \mathbf{neq} \times \mathbf{neq} + (j - 1) \times \mathbf{neq} + i - 1$ ].

*On entry:* set to zero.

*On exit:* **DFDY**(*i, j, k*) must contain the partial derivative of  $f_i$  with respect to  $y_j^{(k)}$ , for  $i = 1, 2, \dots, \mathbf{neq}$ ,  $j = 1, 2, \dots, \mathbf{neq}$  and  $k = 0, 1, \dots, \mathbf{m}[j - 1] - 1$ . Only nonzero partial derivatives need be set.

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **fjac**.

**user** – double \*

**iuser** – Integer \*

**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **fjac** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

3: **gafun** – function, supplied by the user *External Function*

**gafun** must evaluate the boundary conditions at the left-hand end of the range, that is functions  $g_i(z(y(a)))$  for given values of  $z(y(a))$ .

The specification of **gafun** is:

```
void gafun (const double ya[], Integer neq, const Integer m[],
           Integer nlbc, double ga[], Nag_Comm *comm)
```

1: **ya**[*dim*] – const double *Input*

**Note:** the dimension, *dim*, of the array **ya** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **YA**(*i, j*) appears in this document, it refers to the array element **ya**[ $j \times \mathbf{neq} + i - 1$ ].

*On entry:* **YA**(*i, j*) contains  $y_i^{(j)}(a)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(a) = y_i(a)$ .

2: **neq** – Integer *Input*

*On entry:* the number of differential equations.

3: **m**[**neq**] – const Integer *Input*

*On entry:* **m**[*i* - 1] contains  $m_i$ , the order of the *i*th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

4: **nlbc** – Integer *Input*

*On entry:* the number of boundary conditions at *a*.

5: **ga**[**nlbc**] – double *Output*

*On exit:* **ga**[*i* - 1] must contain  $g_i(z(y(a)))$ , for  $i = 1, 2, \dots, \mathbf{nlbc}$ .

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **gafun**.

**user** – double \*  
**iuser** – Integer \*  
**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **gafun** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

- 4: **gbfun** – function, supplied by the user *External Function*
- gbfun** must evaluate the boundary conditions at the right-hand end of the range, that is functions  $\bar{g}_i(z(y(b)))$  for given values of  $z(y(b))$ .

The specification of **gbfun** is:

```
void gbfun (const double yb[], Integer neq, const Integer m[],
           Integer nrbc, double gb[], Nag_Comm *comm)
```

1: **yb**[*dim*] – const double *Input*

**Note:** the dimension, *dim*, of the array **yb** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **YB**(*i*, *j*) appears in this document, it refers to the array element **yb**[ $j \times \mathbf{neq} + i - 1$ ].

*On entry:* **YB**(*i*, *j*) contains  $y_i^{(j)}(b)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i] - 1$ .

**Note:**  $y_i^{(0)}(b) = y_i(b)$ .

2: **neq** – Integer *Input*

*On entry:* the number of differential equations.

3: **m**[**neq**] – const Integer *Input*

*On entry:* **m**[*i* - 1] contains  $m_i$ , the order of the *i*th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

4: **nrbc** – Integer *Input*

*On entry:* the number of boundary conditions at *b*.

5: **gb**[**nrbc**] – double *Output*

*On exit:* **gb**[*i* - 1] must contain  $\bar{g}_i(z(y(b)))$ , for  $i = 1, 2, \dots, \mathbf{nrbc}$ .

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **gbfun**.

**user** – double \*  
**iuser** – Integer \*  
**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **gbfun** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

5: **gajac** – function, supplied by the user *External Function*

**gajac** must evaluate the partial derivatives of  $g_i(z(y(a)))$  with respect to the elements of  $z(y(a)) = (y_1(a), y_1^1(a), \dots, y_1^{(m_1-1)}(a), y_2(a), \dots, y_n^{(m_n-1)}(a))$ .

The specification of **gajac** is:

```
void gajac (const double ya[], Integer neq, const Integer m[],
           Integer nlbc, double dgady[], Nag_Comm *comm)
```

1: **ya**[*dim*] – const double *Input*

**Note:** the dimension, *dim*, of the array **ya** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **YA**(*i*, *j*) appears in this document, it refers to the array element **ya**[ $j \times \mathbf{neq} + i - 1$ ].

*On entry:* **YA**(*i*, *j*) contains  $y_i^{(j)}(a)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(a) = y_i(a)$ .

2: **neq** – Integer *Input*

*On entry:* the number of differential equations.

3: **m**[**neq**] – const Integer *Input*

*On entry:* **m**[*i* - 1] contains  $m_i$ , the order of the *i*th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

4: **nlbc** – Integer *Input*

*On entry:* the number of boundary conditions at *a*.

5: **dgady**[*dim*] – double *Input/Output*

**Note:** the dimension, *dim*, of the array **dgady** is  $\mathbf{nlbc} \times \mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **DGADY**(*i*, *j*, *k*) appears in this document, it refers to the array element **dgady**[ $k \times \mathbf{nlbc} \times \mathbf{neq} + (j - 1) \times \mathbf{nlbc} + i - 1$ ].

*On entry:* set to zero.

*On exit:* **DGADY**(*i*, *j*, *k*) must contain the partial derivative of  $g_i(z(y(a)))$  with respect to  $y_j^{(k)}(a)$ , for  $i = 1, 2, \dots, \mathbf{nlbc}$ ,  $j = 1, 2, \dots, \mathbf{neq}$  and  $k = 0, 1, \dots, \mathbf{m}[j - 1] - 1$ . Only nonzero partial derivatives need be set.

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **gajac**.

**user** – double \*

**iuser** – Integer \*

**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **gajac** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

6: **gbjac** – function, supplied by the user *External Function*

**gbjac** must evaluate the partial derivatives of  $\bar{g}_i(z(y(b)))$  with respect to the elements of  $z(y(b)) = (y_1(b), y_1^1(b), \dots, y_1^{(m_1-1)}(b), y_2(b), \dots, y_n^{(m_n-1)}(b))$ .

The specification of **gbjac** is:

```
void gbjac (const double yb[], Integer neq, const Integer m[],
           Integer nrbc, double dgbdy[], Nag_Comm *comm)
```

1: **yb**[*dim*] – const double *Input*

**Note:** the dimension, *dim*, of the array **yb** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **YB**(*i*, *j*) appears in this document, it refers to the array element **yb**[*j* × **neq** + *i* – 1].

*On entry:* **YB**(*i*, *j*) contains  $y_i^{(j)}(b)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(b) = y_i(b)$ .

2: **neq** – Integer *Input*

*On entry:* the number of differential equations.

3: **m**[**neq**] – const Integer *Input*

*On entry:* **m**[*i* – 1] contains  $m_i$ , the order of the *i*th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

4: **nrbc** – Integer *Input*

*On entry:* the number of boundary conditions at *b*.

5: **dgbdy**[*dim*] – double *Input/Output*

**Note:** the dimension, *dim*, of the array **dgbdy** is  $\mathbf{nrbc} \times \mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **DGBDY**(*i*, *j*, *k*) appears in this document, it refers to the array element **dgbdy**[(*k* – 1) × **nrbc** × **neq** + (*j* – 1) × **nrbc** + *i* – 1].

*On entry:* set to zero.

*On exit:* **DGBDY**(*i*, *j*, *k*) must contain the partial derivative of  $\bar{g}_i(z(y(b)))$  with respect to  $y_j^{(k)}(b)$ , for  $i = 1, 2, \dots, \mathbf{nrbc}$ ,  $j = 1, 2, \dots, \mathbf{neq}$  and  $k = 0, 1, \dots, \mathbf{m}[j - 1] - 1$ . Only nonzero partial derivatives need be set.

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **gbjac**.

**user** – double \*

**iuser** – Integer \*

**p** – Pointer

The type Pointer will be void \*. Before calling nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **gbjac** when called from nag\_ode\_bvp\_coll\_nlin\_solve (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

7: **guess** – function, supplied by the user *External Function*

**guess** must return initial approximations for the solution components  $y_i^{(j)}$  and the derivatives  $y_i^{(m_i)}$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ . Try to compute each derivative  $y_i^{(m_i)}$  such that it corresponds to your approximations to  $y_i^{(j)}$ , for  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ . You should **not** call **ffun** to compute  $y_i^{(m_i)}$ .

If `nag_ode_bvp_coll_nlin_solve` (d02tlc) is being used in conjunction with `nag_ode_bvp_coll_nlin_contin` (d02txc) as part of a continuation process, then **guess** is not called by `nag_ode_bvp_coll_nlin_solve` (d02tlc) after the call to `nag_ode_bvp_coll_nlin_contin` (d02txc).

The specification of **guess** is:

```
void guess (double x, Integer neq, const Integer m[], double y[],
           double dym[], Nag_Comm *comm)
```

1: **x** – double *Input*

*On entry:*  $x$ , the independent variable;  $x \in [a, b]$ .

2: **neq** – Integer *Input*

*On entry:* the number of differential equations.

3: **m[neq]** – const Integer *Input*

*On entry:* **m**[ $i - 1$ ] contains  $m_i$ , the order of the  $i$ th differential equation, for  $i = 1, 2, \dots, \mathbf{neq}$ .

4: **y[dim]** – double *Output*

**Note:** the dimension,  $dim$ , of the array **y** is  $\mathbf{neq} \times \max(\mathbf{m}[i])$ .

Where **Y**( $i, j$ ) appears in this document, it refers to the array element **y**[ $j \times \mathbf{neq} + i - 1$ ].

*On exit:* **Y**( $i, j$ ) must contain  $y_i^{(j)}(x)$ , for  $i = 1, 2, \dots, \mathbf{neq}$  and  $j = 0, 1, \dots, \mathbf{m}[i - 1] - 1$ .

**Note:**  $y_i^{(0)}(x) = y_i(x)$ .

5: **dym[neq]** – double *Output*

*On exit:* **dym**[ $i - 1$ ] must contain  $y_i^{(m_i)}(x)$ , for  $i = 1, 2, \dots, \mathbf{neq}$ .

6: **comm** – Nag\_Comm \*

Pointer to structure of type Nag\_Comm; the following members are relevant to **guess**.

**user** – double \*

**iuser** – Integer \*

**p** – Pointer

The type Pointer will be `void *`. Before calling `nag_ode_bvp_coll_nlin_solve` (d02tlc) you may allocate memory and initialize these pointers with various quantities for use by **guess** when called from `nag_ode_bvp_coll_nlin_solve` (d02tlc) (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).

8: **rcomm**[ $dim$ ] – double *Communication Array*

**Note:** the dimension,  $dim$ , of this array is dictated by the requirements of associated functions that must have been previously called. This array **MUST** be the same array passed as argument **rcomm** in the previous call to `nag_ode_bvp_coll_nlin_setup` (d02tvc).

*On entry:* this must be the same array as supplied to `nag_ode_bvp_coll_nlin_setup` (d02tvc) and **must** remain unchanged between calls.

*On exit:* contains information about the solution for use on subsequent calls to associated functions.



- 9: **icomm**[*dim*] – Integer *Communication Array*  
**Note:** the dimension, *dim*, of this array is dictated by the requirements of associated functions that must have been previously called. This array **MUST** be the same array passed as argument **icomm** in the previous call to nag\_ode\_bvp\_coll\_nlin\_setup (d02tvc).  
*On entry:* this must be the same array as supplied to nag\_ode\_bvp\_coll\_nlin\_setup (d02tvc) and **must** remain unchanged between calls.  
*On exit:* contains information about the solution for use on subsequent calls to associated functions.
- 10: **comm** – Nag\_Comm \*  
The NAG communication argument (see Section 2.3.1.1 in How to Use the NAG Library and its Documentation).
- 11: **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 2.3.1.2 in How to Use the NAG Library and its Documentation for further information.

### NE\_BAD\_PARAM

On entry, argument *<value>* had an illegal value.

### NE\_CONVERGENCE\_SOL

All Newton iterations that have been attempted have failed to converge.  
No results have been generated. Check the coding of the functions for calculating the Jacobians of system and boundary conditions.  
Try to provide a better initial solution approximation.

### 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 2.7.6 in How to Use the NAG Library and its Documentation for further information.

### NE\_MISSING\_CALL

Either the setup function has not been called or the communication arrays have become corrupted. No solution will be computed.

### NE\_NO\_LICENCE

Your licence key may have expired or may not have been installed correctly.  
See Section 2.7.5 in How to Use the NAG Library and its Documentation for further information.

### NE\_SING\_JAC

Numerical singularity has been detected in the Jacobian used in the Newton iteration.  
No results have been generated. Check the coding of the functions for calculating the Jacobians of system and boundary conditions.

**NW\_MAX\_SUBINT**

The expected number of sub-intervals required to continue the computation exceeds the maximum specified:  $\langle value \rangle$ .

Results have been generated which may be useful.

Try increasing this number or relaxing the error requirements.

**NW\_NOT\_CONVERGED**

A Newton iteration has failed to converge. The computation has not succeeded but results have been returned for an intermediate mesh on which convergence was achieved.

These results should be treated with extreme caution.

**7 Accuracy**

The accuracy of the solution is determined by the argument **tols** in the prior call to `nag_ode_bvp_coll_nlin_setup` (d02tvc) (see Sections 3 and 9 in `nag_ode_bvp_coll_nlin_setup` (d02tvc) for details and advice). Note that error control is applied only to solution components (variables) and not to any derivatives of the solution. An estimate of the maximum error in the computed solution is available by calling `nag_ode_bvp_coll_nlin_diag` (d02tzc).

**8 Parallelism and Performance**

`nag_ode_bvp_coll_nlin_solve` (d02tlc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

`nag_ode_bvp_coll_nlin_solve` (d02tlc) 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 function. Please also consult the Users' Note for your implementation for any additional implementation-specific information.

**9 Further Comments**

If `nag_ode_bvp_coll_nlin_solve` (d02tlc) returns with **fail.code** = `NE_CONVERGENCE_SOL`, `NE_SING_JAC`, `NW_MAX_SUBINT` or `NW_NOT_CONVERGED` and the call to `nag_ode_bvp_coll_nlin_solve` (d02tlc) was a part of some continuation procedure for which successful calls to `nag_ode_bvp_coll_nlin_solve` (d02tlc) have already been made, then it is possible that the adjustment(s) to the continuation parameter(s) between calls to `nag_ode_bvp_coll_nlin_solve` (d02tlc) is (are) too large for the problem under consideration. More conservative adjustment(s) to the continuation parameter(s) might be appropriate.

**10 Example**

The following example is used to illustrate the treatment of a high-order system, control of the error in a derivative of a component of the original system, and the use of continuation. See also `nag_ode_bvp_coll_nlin_setup` (d02tvc), `nag_ode_bvp_coll_nlin_contin` (d02txc), `nag_ode_bvp_coll_nlin_interp` (d02tyc) and `nag_ode_bvp_coll_nlin_diag` (d02tzc), for the illustration of other facilities.

Consider the steady flow of an incompressible viscous fluid between two infinite coaxial rotating discs. See Ascher *et al.* (1979) and the references therein. The governing equations are

$$\begin{aligned}\frac{1}{\sqrt{R}}f''' + ff''' + gg' &= 0 \\ \frac{1}{\sqrt{R}}g'' + fg' - f'g &= 0\end{aligned}$$

subject to the boundary conditions

$$f(0) = f'(0) = 0, \quad g(0) = \Omega_0, \quad f(1) = f'(1) = 0, \quad g(1) = \Omega_1,$$

where  $R$  is the Reynolds number and  $\Omega_0, \Omega_1$  are the angular velocities of the disks.

We consider the case of counter-rotation and a symmetric solution, that is  $\Omega_0 = 1, \Omega_1 = -1$ . This problem is more difficult to solve, the larger the value of  $R$ . For illustration, we use simple continuation to compute the solution for three different values of  $R$  ( $= 10^6, 10^8, 10^{10}$ ). However, this problem can be addressed directly for the largest value of  $R$  considered here. Instead of the values suggested in Section 5 in `nag_ode_bvp_coll_nlin_contin` (d02txc) for **nmesh**, **ipmesh** and **mesh** in the call to `nag_ode_bvp_coll_nlin_contin` (d02txc) prior to a continuation call, we use every point of the final mesh for the solution of the first value of  $R$ , that is we must modify the contents of **ipmesh**. For illustrative purposes we wish to control the computed error in  $f'$  and so recast the equations as

$$\begin{aligned} y_1' &= y_2 \\ y_2'' &= -\sqrt{R}(y_1 y_2'' + y_3 y_3') \\ y_3'' &= \sqrt{R}(y_2 y_3 - y_1 y_3') \end{aligned}$$

subject to the boundary conditions

$$y_1(0) = y_2(0) = 0, \quad y_3(0) = \Omega, \quad y_1(1) = y_2(1) = 0, \quad y_3(1) = -\Omega, \quad \Omega = 1.$$

For the symmetric boundary conditions considered, there exists an odd solution about  $x = 0.5$ . Hence, to satisfy the boundary conditions, we use the following initial approximations to the solution in **guess**:

$$\begin{aligned} y_1(x) &= -x^2(x - \frac{1}{2})(x - 1)^2 \\ y_2(x) &= -x(x - 1)(5x^2 - 5x + 1) \\ y_3(x) &= -8\Omega(x - \frac{1}{2})^3. \end{aligned}$$

## 10.1 Program Text

```
/* nag_ode_bvp_coll_nlin_solve (d02tlc) Example Program.
 *
 * NAGPRODCODE Version.
 *
 * Copyright 2016 Numerical Algorithms Group.
 *
 * Mark 26, 2016.
 */

#include <stdio.h>
#include <math.h>
#include <nag.h>
#include <nag_stdlib.h>
#include <nagd02.h>

typedef struct
{
    double omega;
    double sqrofr;
} func_data;

#ifdef __cplusplus
extern "C"
{
#endif
    static void NAG_CALL ffun(double x, const double y[], Integer neq,
                              const Integer m[], double f[], Nag_Comm *comm);
    static void NAG_CALL fjac(double x, const double y[], Integer neq,
                              const Integer m[], double dfdy[], Nag_Comm *comm);
    static void NAG_CALL gafun(const double ya[], Integer neq,
                               const Integer m[], Integer nlbc, double ga[],
                               Nag_Comm *comm);
    static void NAG_CALL gbfun(const double yb[], Integer neq,
                               const Integer m[], Integer nrbc, double gb[],
                               Nag_Comm *comm);
    static void NAG_CALL gajac(const double ya[], Integer neq,
```

```

                                const Integer m[], Integer nlbc, double dgady[],
                                Nag_Comm *comm);
static void NAG_CALL gbjac(const double yb[], Integer neq,
                            const Integer m[], Integer nrbc, double dgbdy[],
                            Nag_Comm *comm);
static void NAG_CALL guess(double x, Integer neq, const Integer m[],
                            double y[], double dym[], Nag_Comm *comm);
#ifdef __cplusplus
}
#endif

int main(void)
{
    /* Scalars */
    double one = 1.0;
    Integer exit_status = 0, neq = 3, mmax = 3, nlbc = 3, nrbc = 3;
    double dx, erm, r, omega;
    Integer i, ierm, ijerm, j, k, licomm, lrcomm, mxmesh, ncol, ncont, nmesh;
    /* Arrays */
    static double ruser[7] = { -1.0, -1.0, -1.0, -1.0, -1.0, -1.0, -1.0 };
    double rdum[1];
    Integer idum[2];
    double *mesh = 0, *tol = 0, *rcomm = 0, *y = 0;
    Integer *ipmesh = 0, *icomm = 0, *m = 0;
    func_data fd;
    /* Nag Types */
    Nag_Comm comm;
    NagError fail;

    INIT_FAIL(fail);

    printf("nag_ode_bvp_coll_nlin_solve (d02tlc) Example Program Results\n\n");

    /* For communication with user-supplied functions: */
    comm.user = ruser;

    /* Skip heading in data file */
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif

#ifdef _WIN32
    scanf_s("%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%*[\n] ", &ncol, &nmesh,
            &mxmesh);
#else
    scanf("%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%*[\n] ", &ncol, &nmesh,
            &mxmesh);
#endif

    if (!(mesh = NAG_ALLOC(mxmesh, double)) ||
        !(m = NAG_ALLOC(neq, Integer)) ||
        !(tol = NAG_ALLOC(neq, double)) ||
        !(y = NAG_ALLOC(neq * mmax, double)) ||
        !(ipmesh = NAG_ALLOC(mxmesh, Integer)))
    {
        printf("Allocation failure\n");
        exit_status = -1;
        goto END;
    }

    /* Set problem equation orders. */
    m[0] = 1;
    m[1] = 3;
    m[2] = 2;

#ifdef _WIN32
    scanf_s("%lf%*[\n] ", &omega);
#else
    scanf("%lf%*[\n] ", &omega);
#endif

```

```

#endif

#ifdef _WIN32
    for (i = 0; i < neq; i++)
        scanf_s("%lf", &tol[i]);
#else
    for (i = 0; i < neq; i++)
        scanf("%lf", &tol[i]);
#endif
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif

    dx = one / (double) (nmesh - 1);
    mesh[0] = 0.0;
    ipmesh[0] = 1;
    for (i = 1; i < nmesh - 1; i++) {
        mesh[i] = mesh[i - 1] + dx;
        ipmesh[i] = 2;
    }
    mesh[nmesh - 1] = one;
    ipmesh[nmesh - 1] = 1;

    /* Query to get size of rcomm and icomm (by setting lrcomm=0) */
    /* nag_ode_bvp_coll_nlin_setup (d02tvc).
     * Ordinary differential equations, general nonlinear boundary value problem,
     * setup for nag_ode_bvp_coll_nlin_solve (d02tlc).
     */
    nag_ode_bvp_coll_nlin_setup(neq, m, nlbc, nrbc, ncol, tol, mxmesh, nmesh,
                               mesh, ipmesh, rdum, 0, idum, 2, &fail);
    if (fail.code == NE_NOERROR) {
        lrcomm = idum[0];
        licomm = idum[1];
        printf("lrcomm = %" NAG_IFMT ", licomm = %" NAG_IFMT "\n", lrcomm,
              licomm);
        if (!(rcomm = NAG_ALLOC(lrcomm, double))
            || !(icomm = NAG_ALLOC(licomm, Integer)))
        {
            printf("Allocation failure\n");
            exit_status = -2;
            goto END;
        }

        /* Initialize again using nag_ode_bvp_coll_nlin_setup (d02tvc). */
        nag_ode_bvp_coll_nlin_setup(neq, m, nlbc, nrbc, ncol, tol, mxmesh, nmesh,
                                    mesh, ipmesh, rcomm, lrcomm, icomm, licomm,
                                    &fail);
    }
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_ode_bvp_coll_nlin_setup (d02tvc).\n%s\n",
              fail.message);
        exit_status = 1;
        goto END;
    }

    /* Number of continuation steps (last r=100**ncont, sqrofr=10**ncont) */
#ifdef _WIN32
    scanf_s("%" NAG_IFMT "%*[\n] ", &ncont);
#else
    scanf("%" NAG_IFMT "%*[\n] ", &ncont);
#endif
    /* Initialize problem continuation parameter. */
#ifdef _WIN32
    scanf_s("%lf%*[\n] ", &r);
#else
    scanf("%lf%*[\n] ", &r);
#endif

    /* Set data required for the user-supplied functions */

```

```

fd.omega = omega;
fd.sqrofr = sqrt(r);
/* Associate the data structure with comm.p */
comm.p = (Pointer) &fd;

for (j = 0; j < ncont; j++) {
    printf("\n Tolerance = %8.1e  r = %10.3e\n", tol[0], r);
    /* Solve problem. */

    /* nag_ode_bvp_coll_nlin_solve (d02tlc).
    * Ordinary differential equations, general nonlinear boundary value
    * problem, collocation technique.
    */
    nag_ode_bvp_coll_nlin_solve(ffun, fjac, gafun, gbfun, gajac, gbjac, guess,
                                rcomm, icomm, &comm, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_ode_bvp_coll_nlin_solve (d02tlc).\n%s\n",
              fail.message);
        exit_status = 2;
        goto END;
    }

    /* Extract mesh */

    /* nag_ode_bvp_coll_nlin_diag (d02tzc).
    * Ordinary differential equations, general nonlinear boundary value
    * problem, diagnostics for nag_ode_bvp_coll_nlin_solve (d02tlc).
    */
    nag_ode_bvp_coll_nlin_diag(mxmesh, &nmesh, mesh, ipmesh, &ermx, &iermx,
                                &ijermx, rcomm, icomm, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_ode_bvp_coll_nlin_diag (d02tzc).\n%s\n",
              fail.message);
        exit_status = 3;
        goto END;
    }

    /* Print mesh and error statistics. */
    printf("\n Used a mesh of %4" NAG_IFMT " points\n", nmesh);
    printf(" Maximum error = %10.2e in interval %4" NAG_IFMT " for component"
           " %4" NAG_IFMT "\n\n", ermx, iermx, ijermx);
    printf(" Mesh points:\n");
    for (i = 0; i < nmesh; i++) {
        printf("%4" NAG_IFMT "(%1" NAG_IFMT ")", i + 1, ipmesh[i]);
        printf("%12.4e%s", mesh[i], i % 4 == 3 ? "\n" : " ");
    }
    /* Print solution components on mesh. */
    printf("\n\n      x      f      f'      g\n");
    for (i = 0; i < nmesh; i++) {

        /* nag_ode_bvp_coll_nlin_interp (d02tyc).
        * Ordinary differential equations, general nonlinear boundary value
        * problem, interpolation for nag_ode_bvp_coll_nlin_solve (d02tlc).
        */
        nag_ode_bvp_coll_nlin_interp(mesh[i], y, neq, mmax, rcomm, icomm,
                                    &fail);
        if (fail.code != NE_NOERROR) {
            printf("Error from nag_ode_bvp_coll_nlin_interp (d02tyc).\n%s\n",
                  fail.message);
            exit_status = 4;
            goto END;
        }

        printf("%8.3f ", mesh[i]);
        for (k = 0; k < neq; k++)
            printf("%9.4f", y[k]);
        printf("\n");
    }
    if (j == ncont - 1) {
        goto END;
    }
}

```

```

/* Modify continuation parameter. */
r = 100.0 * r;
fd.sqrofr = sqrt(r);

/* Select mesh for continuation and call continuation primer routine. */
for (i = 1; i < nmesh - 1; i++) {
    ipmesh[i] = 2;
}
/* nag_ode_bvp_coll_nlin_contin (d02txc).
 * Ordinary differential equations, general nonlinear boundary value
 * problem, continuation facility for nag_ode_bvp_coll_nlin_solve (d02tlc).
 */
nag_ode_bvp_coll_nlin_contin(mxmesh, nmesh, mesh, ipmesh, rcomm, icomm,
                            &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_ode_bvp_coll_nlin_contin (d02txc).\n%s\n",
          fail.message);
    exit_status = 5;
    goto END;
}
}

END:
NAG_FREE(mesh);
NAG_FREE(m);
NAG_FREE(tol);
NAG_FREE(rcomm);
NAG_FREE(y);
NAG_FREE(ipmesh);
NAG_FREE(icomm);
return exit_status;
}

static void NAG_CALL ffun(double x, const double y[], Integer neq,
                        const Integer m[], double f[], Nag_Comm *comm)
{
    func_data *fd = (func_data *) comm->p;
    double y22 = y[1 + 2 * neq];
    double y31 = y[2 + 1 * neq];
    if (comm->user[0] == -1.0) {
        printf("(User-supplied callback ffun, first invocation.)\n");
        comm->user[0] = 0.0;
    }
    f[0] = y[1];
    f[1] = -(y[0] * y22 + y[2] * y31) * fd->sqrofr;
    f[2] = (y[1] * y[2] - y[0] * y31) * fd->sqrofr;
}

static void NAG_CALL fjac(double x, const double y[], Integer neq,
                        const Integer m[], double dfdy[], Nag_Comm *comm)
{
    func_data *fd = (func_data *) comm->p;
    double y22 = y[1 + 2 * neq];
    double y31 = y[2 + 1 * neq];

    if (comm->user[1] == -1.0) {
        printf("(User-supplied callback fjac, first invocation.)\n");
        comm->user[1] = 0.0;
    }

    dfdy[0 + 1 * neq + 0 * neq * neq] = 1.0;
    dfdy[1 + 0 * neq + 0 * neq * neq] = -y22 * fd->sqrofr;
    dfdy[1 + 1 * neq + 2 * neq * neq] = -y[0] * fd->sqrofr;
    dfdy[1 + 2 * neq + 0 * neq * neq] = -y31 * fd->sqrofr;
    dfdy[1 + 2 * neq + 1 * neq * neq] = -y[2] * fd->sqrofr;
    dfdy[2 + 0 * neq + 0 * neq * neq] = -y31 * fd->sqrofr;
    dfdy[2 + 1 * neq + 0 * neq * neq] = -y[2] * fd->sqrofr;
    dfdy[2 + 2 * neq + 0 * neq * neq] = y[1] * fd->sqrofr;
    dfdy[2 + 2 * neq + 1 * neq * neq] = -y[0] * fd->sqrofr;
}

static void NAG_CALL gafun(const double ya[], Integer neq, const Integer m[],

```

```

        Integer nlbc, double ga[], Nag_Comm *comm)
{
    func_data *fd = (func_data *) comm->p;
    if (comm->user[2] == -1.0) {
        printf("(User-supplied callback gafun, first invocation.)\n");
        comm->user[2] = 0.0;
    }
    ga[0] = ya[0];
    ga[1] = ya[1];
    ga[2] = ya[2] - fd->omega;
}

static void NAG_CALL gbfun(const double yb[], Integer neq, const Integer m[],
                          Integer nrbc, double gb[], Nag_Comm *comm)
{
    func_data *fd = (func_data *) comm->p;
    if (comm->user[3] == -1.0) {
        printf("(User-supplied callback gbfun, first invocation.)\n");
        comm->user[3] = 0.0;
    }
    gb[0] = yb[0];
    gb[1] = yb[1];
    gb[2] = yb[2] + fd->omega;
}

static void NAG_CALL gajac(const double ya[], Integer neq, const Integer m[],
                          Integer nlbc, double dgady[], Nag_Comm *comm)
{
    if (comm->user[4] == -1.0) {
        printf("(User-supplied callback gajac, first invocation.)\n");
        comm->user[4] = 0.0;
    }
    dgady[0 + 0 * neq] = 1.0;
    dgady[1 + 1 * neq] = 1.0;
    dgady[2 + 2 * neq] = 1.0;
}

static void NAG_CALL gbjac(const double yb[], Integer neq, const Integer m[],
                          Integer nrbc, double dgbdy[], Nag_Comm *comm)
{
    if (comm->user[5] == -1.0) {
        printf("(User-supplied callback gbjac, first invocation.)\n");
        comm->user[5] = 0.0;
    }
    dgbdy[0 + 0 * neq] = 1.0;
    dgbdy[1 + 1 * neq] = 1.0;
    dgbdy[2 + 2 * neq] = 1.0;
}

static void NAG_CALL guess(double x, Integer neq, const Integer m[],
                          double y[], double dym[], Nag_Comm *comm)
{
    func_data *fd = (func_data *) comm->p;
    double xh = x - 0.5;
    double xx1 = x * (x - 1.0);

    if (comm->user[6] == -1.0) {
        printf("(User-supplied callback guess, first invocation.)\n");
        comm->user[6] = 0.0;
    }
    y[0 + 0 * neq] = -xh * pow(xx1, 2);
    y[1 + 0 * neq] = -xx1 * (5.0 * xx1 + 1.0);
    y[1 + 1 * neq] = -2.0 * xh * (10.0 * xx1 + 1.0);
    y[1 + 2 * neq] = -12.0 * (5.0 * xx1 + x);
    y[2 + 0 * neq] = -8.0 * fd->omega * pow(xh, 3);
    y[2 + 1 * neq] = -24.0 * fd->omega * pow(xh, 2);

    dym[0] = y[1];
    dym[1] = -120.0 * xh;
    dym[2] = -56.0 * fd->omega * xh;
}

```



## 10.2 Program Data

```
nag_ode_bvp_coll_nlin_solve (d02t1c) Example Program Data
  7      11      101      : ncol, nmesh, mxmesh
  1.0    : omega
  1.0e-3 1.0e-3 1.0e-3 : tol(1:neq)
  2      : ncont
  1.0e+6 : r
```

## 10.3 Program Results

```
nag_ode_bvp_coll_nlin_solve (d02t1c) Example Program Results
```

```
lrcomm = 3012, licomm = 127
```

```
Tolerance = 1.0e-03 r = 1.000e+06
(User-supplied callback guess, first invocation.)
(User-supplied callback gafun, first invocation.)
(User-supplied callback gajac, first invocation.)
(User-supplied callback gbfun, first invocation.)
(User-supplied callback gbjac, first invocation.)
(User-supplied callback ffun, first invocation.)
(User-supplied callback fjac, first invocation.)
```

```
Used a mesh of 21 points
Maximum error = 2.77e-07 in interval 17 for component 3
```

```
Mesh points:
```

1(1)	0.0000e+00	2(3)	5.0000e-02	3(2)	1.0000e-01	4(3)	1.5000e-01
5(2)	2.0000e-01	6(3)	2.5000e-01	7(2)	3.0000e-01	8(3)	3.5000e-01
9(2)	4.0000e-01	10(3)	4.5000e-01	11(2)	5.0000e-01	12(3)	5.5000e-01
13(2)	6.0000e-01	14(3)	6.5000e-01	15(2)	7.0000e-01	16(3)	7.5000e-01
17(2)	8.0000e-01	18(3)	8.5000e-01	19(2)	9.0000e-01	20(3)	9.5000e-01
21(1)	1.0000e+00						

x	f	f'	g
0.000	0.0000	0.0000	1.0000
0.050	0.0070	0.1805	0.4416
0.100	0.0141	0.0977	0.1886
0.150	0.0171	0.0252	0.0952
0.200	0.0172	-0.0165	0.0595
0.250	0.0157	-0.0400	0.0427
0.300	0.0133	-0.0540	0.0322
0.350	0.0104	-0.0628	0.0236
0.400	0.0071	-0.0683	0.0156
0.450	0.0036	-0.0714	0.0078
0.500	-0.0000	-0.0724	-0.0000
0.550	-0.0036	-0.0714	-0.0078
0.600	-0.0071	-0.0683	-0.0156
0.650	-0.0104	-0.0628	-0.0236
0.700	-0.0133	-0.0540	-0.0322
0.750	-0.0157	-0.0400	-0.0427
0.800	-0.0172	-0.0165	-0.0595
0.850	-0.0171	0.0252	-0.0952
0.900	-0.0141	0.0977	-0.1886
0.950	-0.0070	0.1805	-0.4416
1.000	0.0000	-0.0000	-1.0000

```
Tolerance = 1.0e-03 r = 1.000e+08
```

```
Used a mesh of 41 points
Maximum error = 3.18e-06 in interval 17 for component 3
```

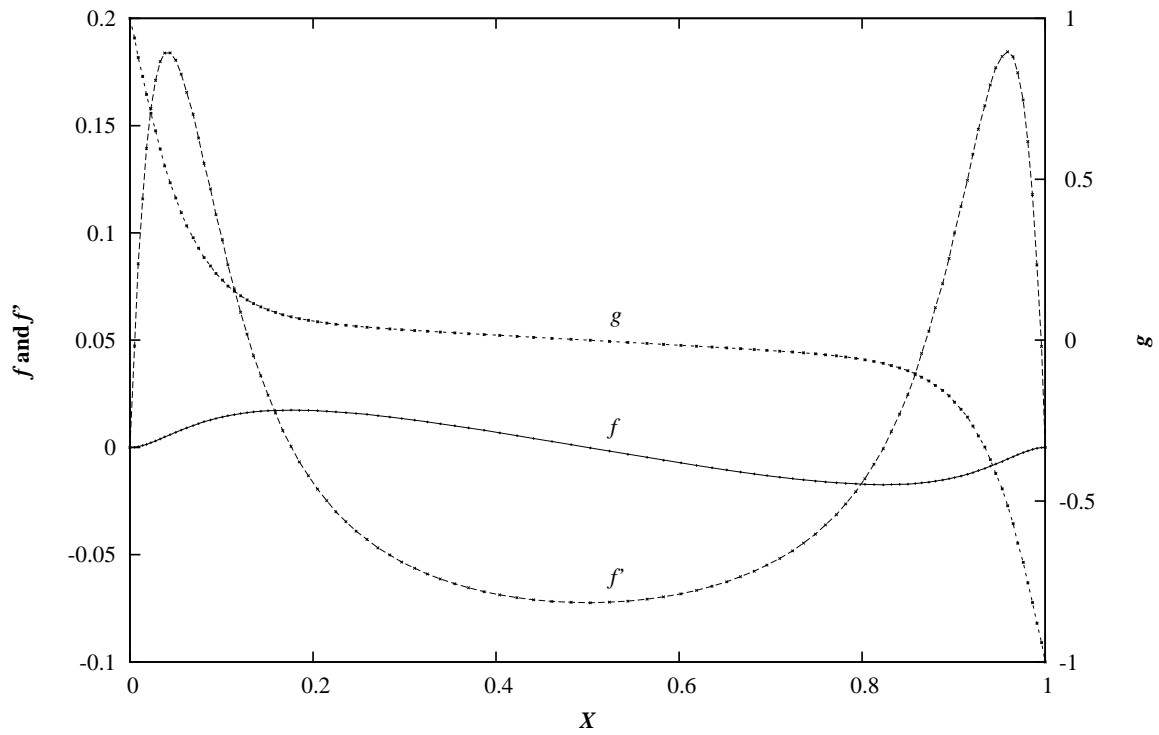
```
Mesh points:
```

1(1)	0.0000e+00	2(3)	7.2063e-03	3(2)	1.4413e-02	4(3)	2.1550e-02
5(2)	2.8687e-02	6(3)	3.5634e-02	7(2)	4.2581e-02	8(3)	5.0435e-02
9(2)	5.8290e-02	10(3)	6.7353e-02	11(2)	7.6416e-02	12(3)	8.8097e-02
13(2)	9.9779e-02	14(3)	1.1602e-01	15(2)	1.3227e-01	16(3)	1.5346e-01

17(2)	1.7465e-01	18(3)	2.0571e-01	19(2)	2.3677e-01	20(3)	2.8658e-01
21(2)	3.3638e-01	22(3)	4.4256e-01	23(2)	5.4874e-01	24(3)	6.3511e-01
25(2)	7.2147e-01	26(3)	7.6429e-01	27(2)	8.0711e-01	28(3)	8.3483e-01
29(2)	8.6254e-01	30(3)	8.8245e-01	31(2)	9.0236e-01	32(3)	9.1689e-01
33(2)	9.3142e-01	34(3)	9.4253e-01	35(2)	9.5364e-01	36(3)	9.6254e-01
37(2)	9.7143e-01	38(3)	9.7877e-01	39(2)	9.8611e-01	40(3)	9.9305e-01
41(1)	1.0000e+00						

x	f	f'	g
0.000	0.0000	0.0000	1.0000
0.007	0.0007	0.1560	0.7032
0.014	0.0019	0.1815	0.4711
0.022	0.0032	0.1561	0.3107
0.029	0.0041	0.1185	0.2044
0.036	0.0048	0.0847	0.1374
0.043	0.0053	0.0580	0.0943
0.050	0.0057	0.0361	0.0641
0.058	0.0059	0.0214	0.0459
0.067	0.0061	0.0104	0.0338
0.076	0.0061	0.0036	0.0271
0.088	0.0061	-0.0015	0.0225
0.100	0.0061	-0.0045	0.0203
0.116	0.0060	-0.0068	0.0188
0.132	0.0059	-0.0082	0.0181
0.153	0.0057	-0.0096	0.0175
0.175	0.0055	-0.0108	0.0169
0.206	0.0051	-0.0123	0.0159
0.237	0.0047	-0.0137	0.0148
0.287	0.0040	-0.0158	0.0126
0.336	0.0031	-0.0175	0.0101
0.443	0.0011	-0.0197	0.0037
0.549	-0.0010	-0.0198	-0.0032
0.635	-0.0026	-0.0183	-0.0085
0.721	-0.0041	-0.0155	-0.0130
0.764	-0.0047	-0.0137	-0.0148
0.807	-0.0053	-0.0117	-0.0163
0.835	-0.0056	-0.0103	-0.0171
0.863	-0.0058	-0.0086	-0.0179
0.882	-0.0060	-0.0070	-0.0187
0.902	-0.0061	-0.0040	-0.0206
0.917	-0.0061	0.0003	-0.0241
0.931	-0.0061	0.0093	-0.0326
0.943	-0.0059	0.0226	-0.0474
0.954	-0.0055	0.0465	-0.0779
0.963	-0.0050	0.0769	-0.1242
0.971	-0.0041	0.1191	-0.2058
0.979	-0.0031	0.1577	-0.3165
0.986	-0.0018	0.1821	-0.4854
0.993	-0.0006	0.1533	-0.7130
1.000	-0.0000	0.0000	-1.0000

**Example Program**  
 Incompressible Fluid Flow between Coaxial Rotating Discs  
 Solutions for Reynolds Number 1,000,000



Incompressible Fluid Flow between Coaxial Rotating Discs  
 Solutions for Reynolds Number 100,000,000

