

ode23t

Trapezoidal rule for solving ordinary differential equations (ODEs) and differential-algebraic equations (DAEs).

Syntax

```
[T,Y] = solver(odefun,tspan,y0)
[T,Y] = solver(odefun,tspan,y0,options)
[T,Y,TE,YE,IE] = solver(odefun,tspan,y0,options)
sol = solver(odefun,[t0 tf],y0...)
```

This page contains an overview of the solver functions: `ode23`, `ode45`, `ode113`, `ode15s`, `ode23s`, `ode23t`, and `ode23tb`. You can call any of these solvers by substituting the placeholder, `solver`, with any of the function names.

Arguments

The following table describes the input arguments to the solvers.

<code>odefun</code>	A function handle that evaluates the right side of the differential equations. All solvers solve systems of equations in the form $y' = f(t,y)$ or problems that involve a mass matrix, $M(t,y)y' = f(t,y)$. The <code>ode23s</code> solver can solve only equations with constant mass matrices. <code>ode15s</code> and <code>ode23t</code> can solve problems with a mass matrix that is singular, i.e., differential-algebraic equations (DAEs).
<code>tspan</code>	<p>A vector specifying the interval of integration, $[t_0, t_f]$. The solver imposes the initial conditions at <code>tspan(1)</code>, and integrates from <code>tspan(1)</code> to <code>tspan(end)</code>. To obtain solutions at specific times (all increasing or all decreasing), use <code>tspan = [t0, t1, ..., tf]</code>.</p> <p>For <code>tspan</code> vectors with two elements $[t_0 \ t_f]$, the solver returns the solution evaluated at every integration step. For <code>tspan</code> vectors with more than two elements, the solver returns solutions evaluated at the given time points. The time values must be in order, either increasing or decreasing.</p>
	<p>Specifying <code>tspan</code> with more than two elements does not affect the internal time steps that the solver uses to traverse the interval from <code>tspan(1)</code> to <code>tspan(end)</code>. All solvers in the ODE suite obtain output values by means of continuous extensions of the basic formulas. Although a solver does not necessarily step precisely to a time point specified in <code>tspan</code>, the solutions produced at the specified time points are of the same order of accuracy as the solutions computed at the internal time points.</p> <p>Specifying <code>tspan</code> with more than two elements has little effect on the efficiency of computation, but for large systems, affects memory management.</p>
<code>y0</code>	A vector of initial conditions.
<code>options</code>	<p>Structure of optional parameters that change the default integration properties. This is the fourth input argument.</p> <pre>[t,y] = solver(odefun,tspan,y0,options)</pre> <p>You can create options using the <code>odeset</code> function. See odeset for details.</p>

The following table lists the output arguments for the solvers.

<code>T</code>	Column vector of time points.
<code>Y</code>	Solution array. Each row in <code>Y</code> corresponds to the solution at a time returned in the corresponding row of <code>T</code> .
<code>TE</code>	The time at which an event occurs.
<code>YE</code>	The solution at the time of the event.
<code>IE</code>	The index <code>i</code> of the event function that vanishes.
<code>sol</code>	Structure to evaluate the solution.

Description

`[T,Y] = solver(odefun,tspan,y0)` with `tspan = [t0 tf]` integrates the system of differential equations $y' = f(t,y)$ from time t_0 to t_f with initial conditions y_0 . The first input argument, `odefun`, is a function handle. The function, $f = \text{odefun}(t,y)$, for a scalar t and a column vector y , must return a column vector f corresponding to $f(t,y)$. Each row in the solution array Y corresponds to a time returned in column vector T . To obtain solutions at the specific times t_0, t_1, \dots, t_f (all increasing or all decreasing), use `tspan = [t0,t1,...,tf]`.

[Parameterizing Functions](#) explains how to provide additional parameters to the function `fun`, if necessary.

`[T,Y] = solver(odefun,tspan,y0,options)` solves as above with default integration parameters replaced by [property values](#) specified in `options`, an argument created with the `odeset` function. Commonly used properties include a scalar relative error tolerance `RelTol` ($1e-3$ by default) and a vector of absolute error tolerances `AbsTol` (all components are $1e-6$ by default). If certain components of the solution must be nonnegative, use the [odeset](#) function to set the `NonNegative` property to the indices of these components. See [odeset](#) for details.

`[T,Y,TE,YE,IE] = solver(odefun,tspan,y0,options)` solves as above while also finding where functions of (t,y) , called event functions, are zero. For each event function, you specify whether the integration is to terminate at a zero and whether the direction of the zero crossing matters. Do this by setting the 'Events' property to a function, e.g., `events` or `@events`, and creating a function `[value,isterminal,direction] = events(t,y)`. For the i th event function in `events`,

- `value(i)` is the value of the function.
- `isterminal(i) = 1`, if the integration is to terminate at a zero of this event function and 0 otherwise.
- `direction(i) = 0` if all zeros are to be computed (the default), $+1$ if only the zeros where the event function increases, and -1 if only the zeros where the event function decreases.

Corresponding entries in `TE`, `YE`, and `IE` return, respectively, the time at which an event occurs, the solution at the time of the event, and the index i of the event function that vanishes.

`sol = solver(odefun,[t0 tf],y0...)` returns a structure that you can use with `deval` to evaluate the solution at any point on the interval $[t_0,t_f]$. You must pass `odefun` as a function handle. The structure `sol` always includes these fields:

<code>sol.x</code>	Steps chosen by the solver.
<code>sol.y</code>	Each column <code>sol.y(:,i)</code> contains the solution at <code>sol.x(i)</code> .
<code>sol.solver</code>	Solver name.

If you specify the `Events` option and events are detected, `sol` also includes these fields:

<code>sol.xe</code>	Points at which events, if any, occurred. <code>sol.xe(end)</code> contains the exact point of a terminal event, if any.
<code>sol.ye</code>	Solutions that correspond to events in <code>sol.xe</code> .
<code>sol.ie</code>	Indices into the vector returned by the function specified in the <code>Events</code> option. The values indicate which event the solver detected.

If you specify an output function as the value of the `OutputFcn` property, the solver calls it with the computed solution after each time step. Four output functions are provided: `odeplot`, `odephas2`, `odephas3`, `odeprint`. When you call the solver with no output arguments, it calls the default `odeplot` to plot the solution as it is computed. `odephas2` and `odephas3` produce two- and three-dimensional phase plane plots, respectively. `odeprint` displays the solution components on the screen. By default, the ODE solver passes all components of the solution to the output function. You can pass only specific components by providing a vector of indices as the value of the `OutputSel` property. For example, if you call the solver with no output arguments and set the value of `OutputSel` to `[1,3]`, the solver plots solution components 1 and 3 as they are computed.

For the stiff solvers `ode15s`, `ode23s`, `ode23t`, and `ode23tb`, the Jacobian matrix $\partial f / \partial y$ is critical to reliability and efficiency. Use [odeset](#) to set Jacobian to `@FJAC` if `FJAC(T,Y)` returns the Jacobian $\partial f / \partial y$ or to the matrix $\partial f / \partial y$ if the Jacobian is constant. If the Jacobian property is not set (the default), $\partial f / \partial y$ is approximated by finite differences. Set the `Vectorized` property 'on' if the ODE function is coded so that `odefun(T,[Y1,Y2 ...])` returns `[odefun(T,Y1),odefun(T,Y2),...]`. If $\partial f / \partial y$ is a sparse matrix, set the `JPattern` property to the sparsity pattern of $\partial f / \partial y$, i.e., a sparse matrix S with $S(i,j) = 1$ if the i th component of $f(t,y)$ depends on the j th component of y , and 0 otherwise.

The solvers of the ODE suite can solve problems of the form $M(t,y)y' = f(t,y)$, with time- and state-dependent mass matrix M . (The `ode23s` solver can solve only equations with constant mass matrices.) If a problem has a mass matrix, create a function

$M = \text{MASS}(t, y)$ that returns the value of the mass matrix, and use [odeset](#) to set the Mass property to @MASS. If the mass matrix is constant, the matrix should be used as the value of the Mass property. Problems with state-dependent mass matrices are more difficult:

- If the mass matrix does not depend on the state variable y and the function MASS is to be called with one input argument, t , set the MStateDependence property to 'none'.
- If the mass matrix depends weakly on y , set MStateDependence to 'weak' (the default); otherwise, set it to 'strong'. In either case, the function MASS is called with the two arguments (t, y) .

If there are many differential equations, it is important to exploit sparsity:

- Return a sparse $M(t, y)$.
- Supply the sparsity pattern of $\partial f / \partial y$ using the JPattern property or a sparse $\partial f / \partial y$ using the Jacobian property.
- For strongly state-dependent $M(t, y)$, set MvPattern to a sparse matrix S with $S(i, j) = 1$ if for any k , the (i, k) component of $M(t, y)$ depends on component j of y , and 0 otherwise.

If the mass matrix M is singular, then $M(t, y)y' = f(t, y)$ is a system of differential algebraic equations. DAEs have solutions only when y_0 is consistent, that is, if there is a vector yp_0 such that $M(t_0, y_0)yp_0 = f(t_0, y_0)$. The ode15s and ode23t solvers can solve DAEs of index 1 provided that y_0 is sufficiently close to being consistent. If there is a mass matrix, you can use [odeset](#) to set the MassSingular property to 'yes', 'no', or 'maybe'. The default value of 'maybe' causes the solver to test whether the problem is a DAE. You can provide yp_0 as the value of the InitialSlope property. The default is the zero vector. If a problem is a DAE, and y_0 and yp_0 are not consistent, the solver treats them as guesses, attempts to compute consistent values that are close to the guesses, and continues to solve the problem. When solving DAEs, it is very advantageous to formulate the problem so that M is a diagonal matrix (a semi-explicit DAE).

Solver	Problem Type	Order of Accuracy	When to Use
ode45	Nonstiff	Medium	Most of the time. This should be the first solver you try.
ode23	Nonstiff	Low	For problems with crude error tolerances or for solving moderately stiff problems.
ode113	Nonstiff	Low to high	For problems with stringent error tolerances or for solving computationally intensive problems.
ode15s	Stiff	Low to medium	If ode45 is slow because the problem is stiff.
ode23s	Stiff	Low	If using crude error tolerances to solve stiff systems and the mass matrix is constant.
ode23t	Moderately Stiff	Low	For moderately stiff problems if you need a solution without numerical damping.
ode23tb	Stiff	Low	If using crude error tolerances to solve stiff systems.

The algorithms used in the ODE solvers vary according to order of accuracy [\[6\]](#) and the type of systems (stiff or nonstiff) they are designed to solve. See [Algorithms](#) for more details.

Options

Different solvers accept different parameters in the options list. For more information, see [odeset](#) and [Integrator Options](#) in the MATLAB® Mathematics documentation.

Parameters	ode45	ode23	ode113	ode15s	ode23s	ode23t	ode23tb
RelTol, AbsTol, NormControl	√	√	√	√	√	√	√

Parameters	ode45	ode23	ode113	ode15s	ode23s	ode23t	ode23tb
OutputFcn, OutputSel, Refine, Stats	√	√	√	√	√	√	√
NonNegative	√	√	√	√*	—	√*	√*
Events	√	√	√	√	√	√	√
MaxStep, InitialStep	√	√	√	√	√	√	√
Jacobian, JPattern, Vectorized	—	—	—	√	√	√	√
Mass	√	√	√	√	√	√	√
MStateDependence	√	√	√	√	—	√	√
MvPattern	—	—	—	√	—	√	√
MassSingular	—	—	—	√	—	√	—
InitialSlope	—	—	—	√	—	√	—
MaxOrder, BDF	—	—	—	√	—	—	—

Note You can use the NonNegative parameter with ode15s, ode23t, and ode23tb only for those problems for which there is no mass matrix.

Examples

Example 1

An example of a nonstiff system is the system of equations describing the motion of a rigid body without external forces.

$$\begin{aligned} y_1' &= y_2 y_3 & y_1(0) &= 0 \\ y_2' &= -y_1 y_3 & y_2(0) &= 1 \\ y_3' &= -0.51 y_1 y_2 & y_3(0) &= 1 \end{aligned}$$

To simulate this system, create a function `rigid` containing the equations

```
function dy = rigid(t,y)
dy = zeros(3,1); % a column vector
dy(1) = y(2) * y(3);
dy(2) = -y(1) * y(3);
dy(3) = -0.51 * y(1) * y(2);
```

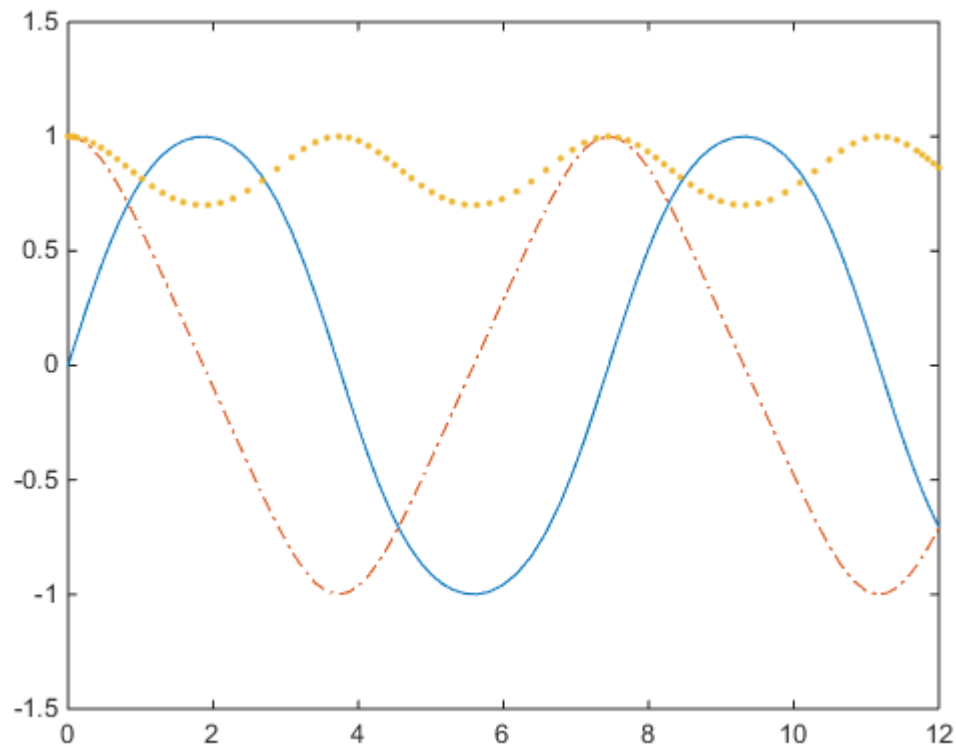
In this example we change the error tolerances using the `odeset` command and solve on a time interval `[0 12]` with an initial condition vector `[0 1 1]` at time 0.

```
options = odeset('RelTol',1e-4,'AbsTol',[1e-4 1e-4 1e-5]);
[T,Y] = ode45(@rigid,[0 12],[0 1 1],options);
```

Plotting the columns of the returned array `Y` versus `T` shows the solution

```
plot(T,Y(:,1),'-',T,Y(:,2),'-.',T,Y(:,3),'.')

```



Example 2

An example of a stiff system is provided by the van der Pol equations in relaxation oscillation. The limit cycle has portions where the solution components change slowly and the problem is quite stiff, alternating with regions of very sharp change where it is not stiff.

$$y_1' = y_2 \quad y_1(0) = 2$$

$$y_2' = 1000(1 - y_1^2)y_2 - y_1 \quad y_2(0) = 0$$

To simulate this system, create a function `vdp1000` containing the equations

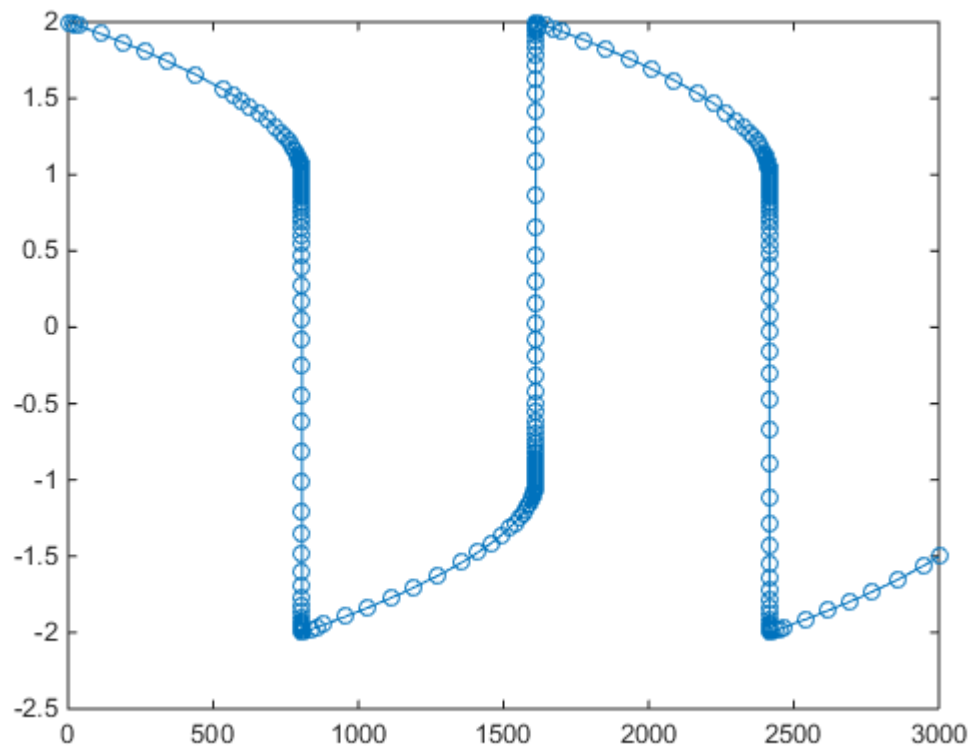
```
function dy = vdp1000(t,y)
dy = zeros(2,1);    % a column vector
dy(1) = y(2);
dy(2) = 1000*(1 - y(1)^2)*y(2) - y(1);
```

For this problem, we will use the default relative and absolute tolerances ($1e-3$ and $1e-6$, respectively) and solve on a time interval of $[0 \ 3000]$ with initial condition vector $[2 \ 0]$ at time 0.

```
[T,Y] = ode15s(@vdp1000,[0 3000],[2 0]);
```

Plotting the first column of the returned matrix `Y` versus `T` shows the solution

```
plot(T,Y(:,1),'-o')
```



Example 3

This example solves an ordinary differential equation with time-dependent terms.

Consider the following ODE, with time-dependent parameters defined only through the set of data points given in two vectors:

$$y'(t) + f(t)y(t) = g(t)$$

The initial condition is $y(1) = 1$, where the function $f(t)$ is defined by the n -by-1 vector f evaluated at times ft , and the function $g(t)$ is defined by the m -by-1 vector g evaluated at times gt .

First, define the time-dependent parameters $f(t)$ and $g(t)$ as the following:

```
ft = linspace(0,5,25); % Generate t for f
f = ft.^2 - ft - 3; % Generate f(t)
gt = linspace(1,6,25); % Generate t for g
g = 3*sin(gt-0.25); % Generate g(t)
```

Write a function to interpolate the data sets specified above to obtain the value of the time-dependent terms at the specified time:

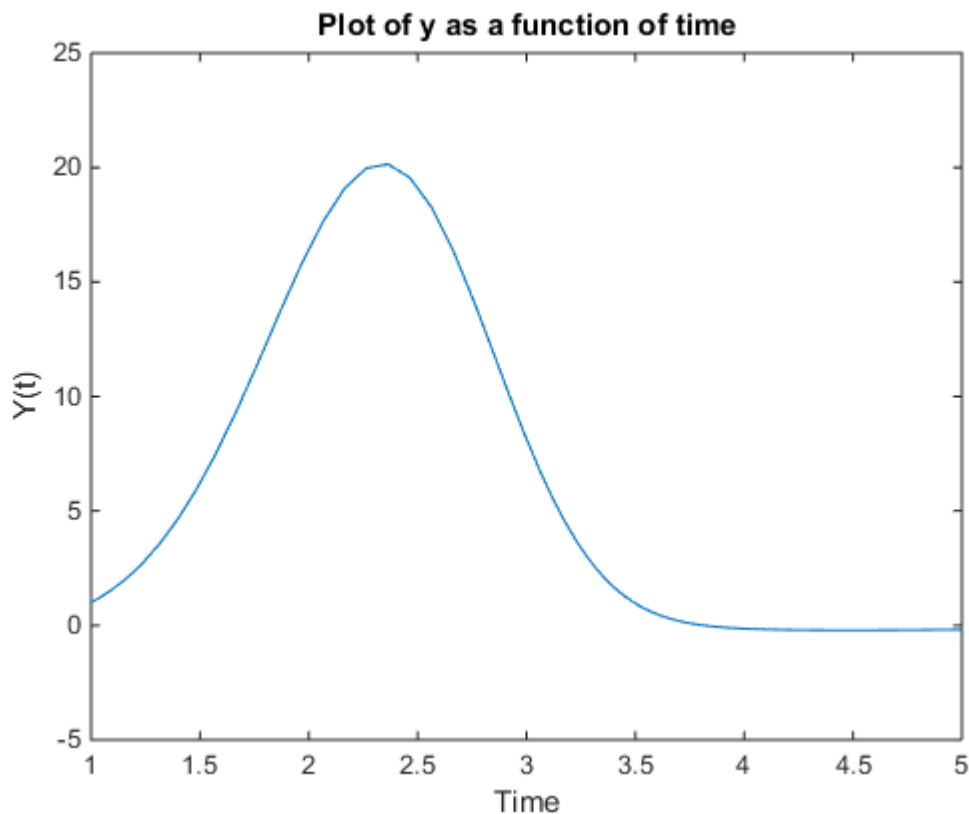
```
function dydt = myode(t,y,ft,f,gt,g)
f = interp1(ft,f,t); % Interpolate the data set (ft,f) at time t
g = interp1(gt,g,t); % Interpolate the data set (gt,g) at time t
dydt = -f.*y + g; % Evaluate ODE at time t
```

Call the derivative function `myode.m` within the MATLAB `ode45` function specifying time as the first input argument :

```
Tspan = [1 5]; % Solve from t=1 to t=5
IC = 1; % y(t=1) = 1
[T Y] = ode45(@myode(t,y,ft,f,gt,g),Tspan,IC); % Solve ODE
```

Plot the solution $y(t)$ as a function of time:

```
plot(T, Y);
title('Plot of y as a function of time');
xlabel('Time');
ylabel('Y(t)');
```



More About

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Algorithms

ode45 is based on an explicit Runge-Kutta (4,5) formula, the Dormand-Prince pair. It is a *one-step* solver – in computing $y(t_n)$, it needs only the solution at the immediately preceding time point, $y(t_{n-1})$. In general, ode45 is the best function to apply as a *first try* for most problems. [3]

ode23 is an implementation of an explicit Runge-Kutta (2,3) pair of Bogacki and Shampine. It may be more efficient than ode45 at crude tolerances and in the presence of moderate stiffness. Like ode45, ode23 is a one-step solver. [2]

ode113 is a variable order Adams-Bashforth-Moulton PECE solver. It may be more efficient than ode45 at stringent tolerances and when the ODE file function is particularly expensive to evaluate. ode113 is a *multistep* solver — it normally needs the solutions at several preceding time points to compute the current solution. [7]

The above algorithms are intended to solve nonstiff systems. If they appear to be unduly slow, try using one of the stiff solvers below.

ode15s is a variable order solver based on the numerical differentiation formulas (NDFs). Optionally, it uses the backward differentiation formulas (BDFs, also known as Gear's method) that are usually less efficient. Like ode113, ode15s is a multistep solver. Try ode15s when ode45 fails, or is very inefficient, and you suspect that the problem is stiff, or when solving a differential-algebraic problem. [9], [10]

ode23s is based on a modified Rosenbrock formula of order 2. Because it is a one-step solver, it may be more efficient than ode15s at crude tolerances. It can solve some kinds of stiff problems for which ode15s is not effective. [9]

ode23t is an implementation of the trapezoidal rule using a "free" interpolant. Use this solver if the problem is only moderately stiff and you need a solution without numerical damping. ode23t can solve DAEs. [10]

ode23tb is an implementation of TR-BDF2, an implicit Runge-Kutta formula with a first stage that is a trapezoidal rule step and a second stage that is a backward differentiation formula of order two. By construction, the same iteration matrix is used in evaluating both stages. Like ode23s, this solver may be more efficient than ode15s at crude tolerances. [8], [1]

- [Create Function Handle](#)

References

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- [2] Bogacki, P. and L. F. Shampine, "A 3(2) pair of Runge-Kutta formulas," *Appl. Math. Letters*, Vol. 2, 1989, pp. 321–325.
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See Also

[deval](#) | [ode15i](#) | [odeget](#) | [odeset](#)

Introduced before R2006a
