Math 5604 Homework 5 and 6

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Problem 1.

Consider the IVP

$$y'' + x^2 y = (x^2 - 4)\sin(2x), \qquad x > 0$$
$$y(0) = 0, \quad y'(0) = 2.$$

In order to solve this IVP numerically, we rewrite it as a system of ODEs by defining $z = y'$. Then we can equivalently solve

$$\begin{aligned} y' &= z \\ z' &= -x^2 y + (x^2 - 4)\sin(2x) \\ y(0) = 0, &\qquad z(0) = 2. \end{aligned}$$

For all numerical solutions, we approximation $y(x_n)$ and $z(x_n)$ by y^n and z^n at the points $\{x_n\}_{n=0}^N$, which are evenly spaced on $[0,1]$ by $k = \frac{1}{N}$.

(a) As the BDF2 method is a two-step method, we need to obtain y^1 and z^1 before we can start the main iteration. For this we can use the backward Euler method, which has second-order local truncation error to match the second-order global truncation error of the BDF2 method. This leads to the following implicit scheme

$$\begin{aligned} y^{n+1} &= \frac{1}{3}\left[4y^n - y^{n-1} + 2kz^{n+1}\right] && n = 1, 2, \dots, N-1 \\ z^{n+1} &= \frac{1}{3}\left[4z^n - z^{n-1} + 2k(-x_{n+1}^2 y^{n+1} + (x_{n+1}^2 - 4)\sin(2x_{n+1}))\right] && n = 1, 2, \dots, N-1 \\ y^1 &= y^0 + kz^1 \\ z^1 &= z^0 + k(-x_1^2 y^1 + (x_1^2 - 4)\sin(2x_1)) \\ y^0 &= 0 \\ z^0 &= 2. \end{aligned}$$

Since the original equation is linear, we can easily solve the implicit equations above to obtain the following equivalent, explicit scheme

$$\begin{aligned} z^{n+1} &= \frac{\frac{1}{3}\left[4z^n - z^{n-1} + 2k\left[-\frac{1}{3}x_{n+1}^2(4y^n - y^{n-1}) + (x_{n+1}^2 - 4)\sin(2x_{n+1})\right]\right]}{1 + \frac{4k^2}{9}x_{n+1}^2} && n = 1, 2, \dots, N-1 \\ y^{n+1} &= \frac{1}{3}\left[4y^n - y^{n-1} + 2kz^{n+1}\right] && n = 1, 2, \dots, N-1 \\ z^1 &= \frac{z^0 + k(-x_1^2 y^0 + (x_1^2 - 4))\sin(2x_1)}{1 + k^2 x_1^2} \\ y^1 &= y^0 + kz^1 \\ y^0 &= 0 \\ z^0 &= 2. \end{aligned}$$

(b)

(c) Since the TR-BDF2 method is a one-step method, we immediately obtain the following implicit scheme

$$
\begin{aligned}
y_*^{n+1} &= y^n + \frac{k}{4}\left[z^n + z_*^{n+1}\right] \\
z_*^{n+1} &= z^n + \frac{k}{4}\left[-x_n^2 y^n + (x_n^2 - 4)\sin(2x_n) - x_{n+1/2}^2 y_*^{n+1} + (x_{n+1/2}^2 - 4)\sin(2x_{n+1/2})\right] \\
y^{n+1} &= \frac{1}{3}\left[4y_*^{n+1} - y^n + kz^{n+1}\right] \\
z^{n+1} &= \frac{1}{3}\left[4z_*^{n+1} - z^n + k\left[-x_{n+1}^2 y^{n+1} + (x_{n+1}^2 - 4)\sin(2x_{n+1})\right]\right] \\
&\quad \text{for } n = 0, 1, \ldots, N-1, \text{ and} \\
y^0 &= 0 \\
z^0 &= 2,
\end{aligned}
$$

where $x_{n+1/2} = x_n + \frac{k}{2}$. As in part (a), we can solve this scheme to obtain an equivalent explicit scheme

$$
\begin{aligned}
z_*^{n+1} &= \frac{z^n + \frac{k}{4}\left[-x_n^2 y^n + (x_n^2 - 4)\sin(2x_n) - x_{n+1/2}^2\left(y^n + \frac{k}{4}z^n\right) + (x_{n+1/2}^2 - 4)\sin(2x_{n+1/2})\right]}{1 + \frac{k^2}{16}x_{n+1/2}^2} \\
y_*^{n+1} &= y^n + \frac{k}{4}\left[z^n + z_*^{n+1}\right] \\
z^{n+1} &= \frac{\frac{1}{3}\left[4z_*^{n+1} - z^n + k\left[-\frac{x_{n+1}^2}{3}\left[4y_*^{n+1} - y^n\right] + (x_{n+1}^2 - 4)\sin(2x_{n+1})\right]\right]}{1 + \frac{k^2}{9}x_{n+1}^2} \\
y^{n+1} &= \frac{1}{3}\left[4y_*^{n+1} - y^n + kz^{n+1}\right] \\
&\quad \text{for } n = 0, 1, \ldots, N-1, \text{ and} \\
y^0 &= 0 \\
z^0 &= 2.
\end{aligned}
$$

(d)

Problem 2.

Consider the BVP

$$
\begin{aligned}
y'' + x^2 y = (x^2 - 4)\sin(2x), &\qquad 0 < x < \pi \\
y(0) = 0, &\qquad y'(\pi) + 2y(\pi) = 2.
\end{aligned}
$$

For all numerical solutions, we approximation $y(x_n)$ by y_n at the points $\{x_n\}_{n=0}^N$, which are evenly spaced on $[0, 1]$ by $h = \frac{1}{N}$.

(a) Using the centered difference method to approximate y'' on the interior of the domain, we get the following scheme for the interior points $y_1, y_2, \ldots y_{N-1}$

$$
\frac{y_{n+1} - 2y_n + y_{n-1}}{h^2} + x_n^2 y_n = (x_n^2 - 4)\sin(2x_n), \qquad n = 1, 2, \ldots, N-1.
$$

The left boundary condition gives the discrete condition $y_0 = 0$, but the right boundary condition involves the first order derivative y'; to approximate this with a centered difference, we would need a point $x_{N+1} = x_N + h$ outside of the domain (assuming that y' can be continuously extended, giving us the approximation $y_{N+1} \approx y(x_{N+1})$). By enforcing the differential equation at the point x_N, we can obtain another equation involving the point x_{N+1}, which we can combine with the boundary condition to eliminate the need for information at x_{N+1}, as follows:

$$\frac{y_{N+1} - y_{N-1}}{2h} + 2y_N = 2 \qquad \text{(right boundary condition)}$$
$$\frac{y_{N+1} - 2y_N + y_{N-1}}{h^2} + x_N^2 y_N = (x_N^2 - 4)\sin(2x_N) \qquad \text{(equation at } x_N\text{)}$$

Eliminating y_{N+1} gives

$$\frac{2y_N - 2y_{N-1} + h^2\left[-x_N^2 y_N + (x_N^2 - 4)\sin(2x_N)\right]}{2h} + 2y_N = 2.$$

Substituting the explicit condition $y_0 = 0$ into the $n = 1$ equation and collecting all our equations together, we obtain the scheme

$$\begin{aligned}
\left(x_1^2 - \frac{2}{h^2}\right) y_1 + \frac{1}{h^2} y_2 &= (x_1^2 - 4)\sin(2x_1) \\
\frac{1}{h^2} y_{n-1} + \left(x_n^2 - \frac{2}{h^2}\right) y_n + \frac{1}{h^2} y_{n+1} &= (x_n^2 - 4)\sin(2x_n), \qquad n = 2, 3, \dots, N-1 \\
-\frac{1}{h} y_{N-1} + \left(\frac{1}{h} - \frac{h x_N^2}{2} + 2\right) y_N &= 2 - \frac{h}{2}(x_N^2 - 4)\sin(2x_N).
\end{aligned}$$

We can write this system of equations in matrix-vector form $Ay = b$, where

$$A = \begin{bmatrix}
x_1^2 - \frac{2}{h^2} & \frac{1}{h^2} & & & & \\
\frac{1}{h^2} & x_2^2 - \frac{2}{h^2} & \frac{1}{h^2} & & & \\
& \frac{1}{h^2} & x_3^3 - \frac{2}{h^2} & \frac{1}{h^2} & & \\
& & \ddots & & & \\
& & \frac{1}{h^2} & x_{N-1}^2 - \frac{2}{h^2} & \frac{1}{h^2} \\
& & & -\frac{1}{h} & \frac{1}{h} - \frac{h x_N^2}{2} + 2
\end{bmatrix},$$

where empty entries are assumed to be 0, and

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \qquad b = \begin{bmatrix} (x_1^2 - 4)\sin(2x_1) \\ (x_2^2 - 4)\sin(2x_2) \\ \vdots \\ (x_{N-1}^2 - 4)\sin(2x_{N-1}) \\ 2 - \frac{h}{2}(x_N^2 - 4)\sin(2x_N) \end{bmatrix}.$$

(b)

(c) Using the centered difference method to approximate y'' on the interior of the domain, we get the following scheme for the interior points $y_1, y_2, \dots y_{N-1}$

$$\frac{y_{n+1} - 2y_n + y_{n-1}}{h^2} + x_n^2 y_n = (x_n^2 - 4)\sin(2x_n), \qquad n = 1, 2, \dots, N-1.$$

The left boundary condition gives the discrete condition $y_0 = 0$, but the right boundary condition involves the first order derivative y'; to approximate this with a second-order, one-sided method, we recall from class that, for a function $u(t)$,

$$u'(t) = \frac{-3u(t) + 4u(t+k) - u(t+2k)}{2k} + \mathcal{O}(k^2).$$

Taking $u = y$, $k = -h$, and $t = \pi$, this implies that

$$y'(\pi) = \frac{3y(\pi) - 4y(\pi - h) + y(\pi - 2h)}{2h} + \mathcal{O}(h^2).$$

This leads to the second-order, one-sided discretization of the right boundary condition

$$\frac{3y_N - 4y_{N-1} + y_{N-2}}{2h} + 2y_N = 2.$$

Combining the left boundary condition with the first interior equation, we have the scheme

$$\begin{aligned}
\left(x_1^2 - \frac{2}{h^2}\right) y_1 + \frac{1}{h^2} y_2 &= (x_1^2 - 4)\sin(2x_1) \\
\frac{1}{h^2} y_{n-1} + \left(x_n^2 - \frac{2}{h^2}\right) y_n + \frac{1}{h^2} y_{n+1} &= (x_n^2 - 4)\sin(2x_n), \qquad n = 2, 3, \dots, N-1 \\
\frac{1}{2h} y_{N-2} - \frac{2}{h} y_{N-1} + \left(2 + \frac{3}{2h}\right) y_N &= 2.
\end{aligned}$$

This system of equations can be written in matrix-vector form $Ay = b$, where

$$A = \begin{bmatrix}
x_1^2 - \frac{2}{h^2} & \frac{1}{h^2} & & & \\
\frac{1}{h^2} & x_2^2 - \frac{2}{h^2} & \frac{1}{h^2} & & \\
 & \frac{1}{h^2} & x_3^2 - \frac{2}{h^2} & \frac{1}{h^2} & \\
 & & \ddots & & \\
 & & \frac{1}{h^2} & x_{N-1}^2 - \frac{2}{h^2} & \frac{1}{h^2} \\
 & & \frac{1}{2h} & -\frac{2}{h} & 2 + \frac{3}{2h}
\end{bmatrix},$$

where blank entries are assumed to be 0, and

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \qquad b = \begin{bmatrix} (x_1^2 - 4)\sin(2x_1) \\ (x_2^2 - 4)\sin(2x_2) \\ \vdots \\ (x_{N-1}^2 - 4)\sin(2x_{N-1}) \\ 2 \end{bmatrix}.$$

(d)

Problem 3.

Consider the boundary-value problem

$$\begin{aligned}
&\varepsilon y'' - x^2 y' - y = 0, \qquad 0 < x < 1 \\
&y(0) = 1, \qquad y(1) = 1,
\end{aligned}$$

where $\varepsilon > 0$.

(a) We approximation $y(x_n)$ by y_n at the points $\{x_n\}_{n=0}^N$, which are evenly spaced on $[0,1]$ by $h = \frac{1}{N}$. To handle the boundary conditions, we simply set $y_0 = 1$ and $y_N = 1$. At the interior points, we can use central difference approximations of the derivatives to obtain the equations

$$\varepsilon\frac{y_{n+1} - 2y_n + y_{n-1}}{h^2} - x_n^2\frac{y_{n+1} - y_{n-1}}{2h} - y_n = 0, \qquad n = 1, 2, \dots, N-1.$$

Combining the boundary conditions with the first and last of these equations, we obtain the scheme

$$\begin{aligned}
\left(\frac{\varepsilon}{h^2} - \frac{x_1^2}{2h}\right)y_2 - \left(\frac{2\varepsilon}{h^2} + 1\right)y_1 &= -\left(\frac{\varepsilon}{h^2} + \frac{x_1^2}{2h}\right) && \text{(left BC)}\\
-\left(\frac{2\varepsilon}{h^2} + 1\right)y_{N-1} + \left(\frac{\varepsilon}{h^2} + \frac{x_{N-1}^2}{2h}\right)y_{N-2} &= -\left(\frac{\varepsilon}{h^2} - \frac{x_{N-1}^2}{2h}\right) && \text{(right BC)}\\
\left(\frac{\varepsilon}{h^2} - \frac{x_n^2}{2h}\right)y_{n+1} - \left(\frac{2\varepsilon}{h^2} + 1\right)y_n + \left(\frac{\varepsilon}{h^2} + \frac{x_n^2}{2h}\right)y_{n-1} &= 0, && n = 2, 3, \dots, N-2.
\end{aligned}$$

We can write these equations in matrix-vector form $Ay = b$, where

$$A = \begin{bmatrix}
-\frac{2\varepsilon}{h^2} - 1 & \frac{\varepsilon}{h^2} - \frac{x_1^2}{2h} & & & & \\
\frac{\varepsilon}{h^2} + \frac{x_2^2}{2h} & -\frac{2\varepsilon}{h^2} - 1 & \frac{\varepsilon}{h^2} - \frac{x_2^2}{2h} & & & \\
& \frac{\varepsilon}{h^2} + \frac{x_3^2}{2h} & -\frac{2\varepsilon}{h^2} - 1 & \frac{\varepsilon}{h^2} - \frac{x_3^2}{2h} & & \\
& & \ddots & & & \\
& & \frac{\varepsilon}{h^2} + \frac{x_{N-2}^2}{2h} & -\frac{2\varepsilon}{h^2} - 1 & \frac{\varepsilon}{h^2} - \frac{x_{N-2}^2}{2h} \\
& & & \frac{\varepsilon}{h^2} + \frac{x_{N-1}^2}{2h} & -\frac{2\varepsilon}{h^2} - 1
\end{bmatrix},$$

where blank entries are assumed to be 0, and

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{N-1} \end{bmatrix}, \qquad b = \begin{bmatrix} -\left(\frac{\varepsilon}{h^2} + \frac{x_1^2}{2h}\right) \\ 0 \\ \vdots \\ 0 \\ -\left(\frac{\varepsilon}{h^2} - \frac{x_{N-1}^2}{2h}\right) \end{bmatrix}.$$

(b)

(c)

(d)

(e)