An Evaluation Of A Multigrid Algorithm Error Spike Correction Method

Erika L. McMichael

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An Evaluation Of A Multigrid Algorithm Error Spike Correction Method

by

Erika L. McMichael

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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Erika L. McMichael

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Abstract

This study is an evaluation of a method of improving the multigrid process by correcting error spikes which are generated when moving from a coarser to finer level. The correction method was tested on nine one-dimensional problems governed by second order differential equations. Tests were performed with an accomodative, full approximation scheme, full multi-grid algorithm.

Results indicate that appropriate implementation of the correction can increase solution accuracy. Accuracy was increased in 75% of cases in which a single correction was applied to a point in the central portion of the grid. Single corrections performed on points with error greater than the average error were effective 86% of the time. Further study is required to determine a method of identifying this scenario.
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Chapter 1

Introduction

Multigrid is an iterative method which utilizes grids of multiple sizes to reduce error on multiple wavelengths. Many classical iterative methods (Gauss Seidel, etc.) efficiently reduce the error of high frequency components, "smoothing" the error. Multigrid uses a relaxation scheme to smooth the error on several grid levels of varying coarseness. In this way, multigrid can greatly reduce the time required to obtain a solution. Brandt introduced multigrid methods in his 1977 paper [1]. Since that time several books have been written on the topic, including [6], [5], [3], and [4].

In this study the multigrid process was examined graphically through plots of the residuals and error after each iteration in the multigrid cycle. From the examination of these plots it became apparent that spikes in the residual plots corresponded to spikes in the error plots. It was also noted that error spikes were prevalent when moving to finer grid levels. A correction method designed to mitigate these error spikes is described in this thesis. Testing showed that the removal of a single error spike could increase the accuracy of the solution while only minimally increasing the amount of computational work.

To evaluate the effectiveness of the correction method, a multigrid program was written and nine one-dimensional problems were tested. The multigrid program utilized an accomodative, full approximation scheme, full multi-grid algorithm (FAS FMG). Brandt provides a detailed description of an accomodative FAS FMG algorithm in [2]. One-dimensional problems were used for simplicity. For consistency, the problems evaluated were all second order differential equations. The differential equation solutions include five polynomials, three trigonometric functions, and one exponential function. The effects of several independent variables (such as grid level, location on grid, etc.) on solution accuracy and number of iterations required for convergence were recorded and are presented here.

A brief introduction to computational fluid dynamics (CFD) is given in Chapter 2 of this thesis. The basic multigrid process is outlined in Chapter 3, and the multi-grid program used in this study is described in Chapter 4. Chapter 5 describes the proposed correction method and discusses the computational work required for its
implementation. The problems used in the study are presented in Chapter 6. Testing methods are discussed in Chapter 7, and results are reported in Chapter 8.
Chapter 2

Computational Fluid Dynamics

Many fluid flow problems cannot be solved analytically. These problems can be solved numerically using computational fluid dynamics. Computational fluid dynamics (CFD) is the term given to a variety of numerical mathematical techniques used to solve the equations that govern fluid flows and aerodynamics. CFD was developed in the 1970s after the introduction of high-speed computers.

Because CFD solvers use numerical methods to obtain a solution, the region being analyzed must be divided into a grid with discrete grid points. A numerical solution is obtained at each of the grid points. To use CFD to solve a problem, the governing equations must be discretized so that the values of the variables are considered at the grid point only. If there are n grid points on the grid, n algebraic equations are developed by discretizing the governing differential equations. Several discretization schemes exist. In this thesis, differential equations were discretized using central differencing derived from the Taylor series expansion (5.1), (5.2). Other types of discretization include forward and backward differencing as well as forward, backward, or central differencing using a larger number of grid points (for example three and four point formulae).

When a problem is discretized it changes from a differential equation to a set of algebraic equations. If the problem is nonlinear it must be linearized before it can be solved using the methods described in this thesis. For simplicity, only linear problems are discussed in this thesis. If the set of equations is linear it can be represented in matrix form as:

$$Au = f$$

(2.1)

where, $A$ is the known coefficient matrix, $u$ is the vector of $n$ dependent variables, and $f$ is the vector of known values. Equation (2.1) can be solved using direct or iterative methods. Direct methods use a finite number of operations to obtain a solution and iterative methods use a variable number of iterations depending on the accuracy desired. The number of iterations is controlled by the stopping criteria, usually an average of the residuals (the difference between $f$ and $Au$ at each point). Multigrid methods and the Gauss Seidel iteration are iterative methods. The Gauss
Seidel iteration is given in equation (4.1).

Boundary conditions are specified conditions on the edges of the domain which aid in the solution of partial differential equations. Common boundary condition types are Dirichlet, Neumann, and Cauchy boundary conditions. Dirichlet boundary conditions specify the values of the function on the boundary. Neumann boundary conditions specify the derivative of the function on the boundary. Cauchy boundary conditions specify a weighted average of Dirichlet and Neumann boundary conditions. When Neumann boundary conditions are specified the boundary conditions are part of the computational domain (the computational domain is the area of the grid where the values of the dependent variable are unknown). Boundary grid points with Dirichlet boundary conditions are not included in the computational domain.

The following example illustrates the process of discretizing the partial differential equation (2.3) and expressing it in the matrix form \( Au = f \) (2.6). The example applies the steady state heat conduction equation (Laplace equation) (2.2) to a plate with an unknown temperature distribution, known edge temperatures, and no heat generation. In (2.2) \( u \) is the temperature (the dependent variable) and the dimensions of the plate are \( L \times L \). The temperature is constant along each edge of the plate. The temperatures on the edges of the plate are the boundary conditions and are designated \( B_1, B_2, B_3, B_4 \). For example, \( u = B_1 \) at \( x = 0 \) and \( u = B_2 \) at \( y = L \). The example has Dirichlet boundary conditions (known boundary values). The 2-dimensional plate being analyzed is shown divided into a grid in Figure 2.1. The distance between grid points in the \( x \) and \( y \) directions are denoted by \( \Delta x \) and \( \Delta y \) respectively. In this case \( \Delta x = \Delta y = \frac{L}{3} \). There are four points in the computational domain \( (n = 4) \) which are labeled \( u_1, u_2, u_3, \) and \( u_4 \). The grid coordinates are denoted by \( (i,j) \).

\[
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 \quad (2.2)
\]

\[
\frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{\Delta x^2} + \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1}}{\Delta y^2} = 0 \quad (2.3)
\]

\[
u_{i+1,j} + u_{i-1,j} - 4u_{i,j} + u_{i,j+1} + u_{i,j-1} = 0 \quad (2.4)
\]

Grid point \((\frac{L}{3}, \frac{2L}{3})\): \[u_3 + B_1 - 4u_1 + B_2 + u_2 = 0\]

Grid point \((\frac{L}{3}, \frac{L}{3})\): \[u_4 + B_1 - 4u_2 + u_1 + B_4 = 0\]

Grid point \((\frac{2L}{3}, \frac{2L}{3})\): \[B_3 + u_1 - 4u_3 + B_2 + u_4 = 0\]

Grid point \((\frac{2L}{3}, \frac{L}{3})\): \[B_3 + u_2 - 4u_4 + u_3 + B_4 = 0\]

(2.5)
Figure 2.1: Example grid.

\[
\begin{bmatrix}
-4 & 1 & 1 & 0 \\
1 & -4 & 0 & 1 \\
1 & 0 & -4 & 1 \\
0 & 1 & 1 & -4 \\
\end{bmatrix}
\begin{bmatrix}
\hat{u}_1 \\
\hat{u}_2 \\
\hat{u}_3 \\
\hat{u}_4 \\
\end{bmatrix} =
\begin{bmatrix}
\hat{B}_1 - \hat{B}_2 \\
\hat{B}_1 - \hat{B}_4 \\
\hat{B}_3 - \hat{B}_2 \\
\hat{B}_3 - \hat{B}_4 \\
\end{bmatrix}
\]  (2.6)
Chapter 3

Multigrid

Multigrid methods are iterative methods used to solve partial differential equations. Multigrid methods use multiple grids of varying coarseness to speed up convergence. The two main components of multigrid methods are error smoothing and coarse grid correction.

Each grid used in solving the problem is identified by a grid level (for example the coarsest grid is referred to as level 1). On each grid level the error is “smoothed” with the one or more iterations of a relaxation scheme (e.g. Gauss-Seidel). The relaxation methods are efficient at reducing the error (4.9) of high frequency components. Figure 3.1 shows the effects of one and four Gauss-Seidel iterations on a one dimensional problem. The high frequency errors are quickly resolved giving the plot a smooth appearance.

Figure 3.1: Error vs. Grid Point: After initial guess, After 1 GS iteration, After 4 GS iterations.

Once the error on the fine grid is smoothed it is transferred to a coarser grid. The error is smoothed on the coarse grids and the coarse grid approximations are used to correct the finest grid approximation. Applying the relaxation scheme to grids of varying coarseness results in efficient error reduction at multiple frequencies.
3.1 Basic Multigrid Process

This section describes the multigrid process in very general terms. A detailed description of the algorithm used in this study is given in the next chapter. The discretized equation to be solved is (2.1). On the $k^{th}$ grid level the discretized equation is represented as:

$$A^k u^k = f^k$$

Restriction and prolongation operators are used to move between grid levels. Restriction operators are used to transfer to coarser levels and either directly inject or average fine grid values to obtain a coarse grid value. Prolongation operators use interpolation to transfer to finer grids. The restriction and prolongation operators are denoted by $R$ and $P$ respectively.

$$Ru^{k+1} = u^k$$

$$Pu^k = u^{k+1}$$

The first step in the multigrid process is presmoothing, the application of $v_1$ iterations of an appropriate relaxation scheme. This is denoted by:

$$S(u^k, A^k, f^k, v_1)$$

The process then moves to a lower (coarser) grid level. On the lower grid level, $f^k$ is modified and a relaxation scheme is implemented to approximate $u^k$ (3.1). This coarse grid approximation is used to correct the finer grid approximation. The value of $f^k$ and the meaning of $u^k$ depend on the multigrid scheme (see Coarse Grid Processing, below). The final step of the process is postsmoothing, relaxation on the fine grid level. These steps can be performed multiple times on any number of grid levels.

3.2 Multigrid Algorithms

Starting Point

Full Multi-Grid (FMG) algorithms begin on the coarsest level and move up. The coarsest level solution may be obtained by relaxation or a direct method.[2]

Cycling algorithms begin with an approximation on the finest grid. The approximation can be trivial, such as $u = 0$, or the solution of a previous similar problem.[2]
Program Progression

An algorithm is described as accommodative or fixed. Accomodative algorithms use internal checks to determine when a switch will be made to a finer or coarser level. The checks are usually based on relative magnitudes of residuals.

Fixed algorithms have no internal checks and operate based on a predetermined flow. Fixed algorithms may execute more quickly than accomodative algorithms because they do not require the calculation of residuals after each iteration.

Coarse Grid Processing

A multigrid algorithm can use the Correction Scheme or the Full Approximation Scheme described in this section. In the Correction Scheme the long wavelength error of the fine grid approximation \(u^{k+1}\) is approximated on the coarse grid by \(u^k\). On the coarse grid, the right hand side of equation (3.1) is given by (3.6), the restriction of the fine grid residual error \(r^{k+1}\) (3.5). To correct the fine grid approximation \(u^{k+1}\), \(u^k\) is prolongated and added to \(u^{k+1}\) (3.7).[2]

\[
\begin{align*}
    r^{k+1} &= f^{k+1} - A^{k+1} u^{k+1} \quad (3.5) \\
    f^k &= R r^{k+1} \quad (3.6) \\
    u^{k+1}_{\text{new}} &= u^{k+1}_{\text{old}} + P u^k \quad (3.7)
\end{align*}
\]

In the Full Approximation Scheme (FAS) the coarse grid approximation \(u^k\) approximates the solution to the differential equation on level \(k\). When transferring to a coarser level \(k\), an initial value of \(u^k\) is the restriction of \(u^{k+1}\) (3.8). This initial value is used in the calculation of \(f^k\) (3.9). The fine grid is corrected with (3.10).[2]

\[
\begin{align*}
    u^k &= R u^{k+1} \quad (3.8) \\
    f^k &= A^k u^k + R r^{k+1} \quad (3.9) \\
    u_{\text{new}}^{k+1} &= u_{\text{old}}^{k+1} + P(u^k - Ru_{\text{old}}^{k+1}) \quad (3.10)
\end{align*}
\]

The algorithm used is fully described by one item from each of the above three sections. The program used in this study is an accomodative, full approximation scheme, full multi-grid (FAS FMG) algorithm.
Chapter 4

Multigrid Program

A multigrid program written for this study is described in this section. This program provided a means of testing the correction method. The program uses an accommodative full approximation scheme full multi-grid (FAS FMG) algorithm. It is capable of solving one dimensional problems with Dirichlet boundary conditions. The program source code is in Appendix A.

4.1 Basic Elements

Smoothing Method

The Gauss-Seidel iteration is used for error smoothing on all grid levels. For the case of $M$ equations the $n+1^{th}$ round of Gauss-Seidel iterations can be written as:

$$u_{i}^{n+1} = \frac{1}{a_{ii}} \left[ f_{i} - \sum_{j=1}^{i-1} a_{ij} u_{j}^{n+1} - \sum_{j=i+1}^{M} a_{ij} u_{j}^{n} \right] \quad \text{for } i = 1 \text{ to } M \quad (4.1)$$

Gauss-Seidel iterations are performed by the subroutine gs.for, see Appendix A.3.

Prolongation/Restriction Operators

The restriction and prolongation operators used in grid transfer are defined by the following equations:

$$Ru_{j} = \frac{1}{4} u_{2j-1} + \frac{1}{2} u_{2j} + \frac{1}{4} u_{2j+1} \quad \text{Restriction} \quad (4.2)$$

$$Pu_{2j} = u_{j} \quad Pu_{2j+1} = \frac{1}{2} (u_{j} + u_{j+1}) \quad \text{Prolongation} \quad (4.3)$$

These are taken from [6]. Prolongation and restriction matrices are created in the subroutine prores.for, see Appendix A.4.
Coefficient Matrix

The finest level coefficient matrix $A$ from (2.1) is provided by the user. To perform smoothing operations on all grid levels, an $A$ matrix must be obtained for each level. Here the Galerkin coarse grid approximation is used:

$$A^k = RA^{k+1}P$$  \hfill (4.4)

### 4.2 User Inputs

Seven items must be supplied by the user for the program to operate:

1. $n_m$ The number of grid points in the computational domain on the finest level
2. The exact value of the center point of the computational domain
3. $domain$ The length of the grid $(x_{max} - x_{min})$
4. Dirichlet boundary conditions
5. $\varepsilon_m$ Finest level convergence criteria
6. $A$ The coefficient matrix in (2.1)
7. $f$ The vector of known values in (2.1)

### 4.3 Structure

The number of grid levels $m$ used in computation is calculated from $n$, the size of the computational domain (number of grid points) on the finest level. For the program to function $n$ must be able to satisfy (4.5) where $m$ is an integer. The size of the computational domain on levels 1-6 is shown in Table 4.1. Level 1 is the coarsest level.

$$n = 2^m - 1$$  \hfill (4.5)

<table>
<thead>
<tr>
<th>Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>15</td>
<td>31</td>
<td>63</td>
</tr>
</tbody>
</table>

Table 4.1: Size of computational domain per grid level.
The program begins computation on the coarsest level 1 and works up to the finest level \( m \). Level 1 consists of only three grid points. The exact values of these three points are supplied. The two end points are the Dirichlet boundary conditions. The center point is provided by the user. It is assumed that this point can be obtained through iterative or direct methods. Because the values of \( u \) on level 1 \( (u^1) \) are known this level is not revisited.

The prolongation of \( u^1 \) gives an initial estimate for \( u^2 \). One Gauss-Seidel (GS) iteration is then performed on \( u^2 \). Convergence on the current level is then checked as described in section 4.4. If convergence has been obtained on level 2 the program moves up to level 3 \( (3.10) \). If not, another GS iteration is performed on \( u^2 \).

After a transfer is made to any level, one Gauss-Seidel iteration is performed and both convergence and convergence rate are checked as described in section 4.4. If the convergence on the current level has been obtained the program moves to a finer level \( (3.10) \). Otherwise if the relaxation convergence rate is acceptable, another GS iteration is performed on the current level. If the relaxation convergence rate is slow the program moves to a coarser level using \( (3.8) - (3.9) \). This procedure is repeated until the convergence criteria are met on the finest grid level.

### 4.4 Convergence Testing

After each GS iteration, the norm of the residuals \( \varepsilon_k \) \( (4.6) \) is computed and convergence and convergence rate are tested. The convergence criteria for the current operation level is denoted by \( \varepsilon_k \). Convergence has been obtained on the current level if \( \varepsilon_k \leq \varepsilon_k \). Finest level convergence \( \varepsilon_m \) is provided by the user. Initial values of \( \varepsilon_k \) for all other levels are obtained from \( (4.7) \) unless this calculated \( \varepsilon_k \) is smaller than \( \varepsilon_m \), in which case \( \varepsilon_k \) is set equal to \( \varepsilon_m \).

\[
\varepsilon_k = \left[ \frac{\sum_{i=1}^{n_k} x_i^2}{n_k} \right]^{1/2} \quad (4.6)
\]

\[
\varepsilon_k = \left[ \frac{\text{domain}}{n_k + 1} \right]^2 \quad (4.7)
\]

Equation 4.7 sets \( \varepsilon_k \) equal to the distance between grid points squared. Each time a transfer is made to a coarser level \( \varepsilon_k \) is updated:

\[
\varepsilon_k = 0.2 \varepsilon_{k+1} \quad (4.8)
\]

To correct the fine grid solution, the coarse grid residuals should be smaller than the fine grid residuals. [2]
If \( e_k > \varepsilon_k \), convergence rate is tested. The convergence rate is satisfactory if \( e_k \leq \eta \bar{e}_k \), where \( \eta = 0.5 \) and \( \bar{e}_k \) holds previous values of \( e_k \). If the convergence rate is satisfactory \( \bar{e}_k \) is set equal to \( e_k \) \( (\bar{e}_k = e_k) \) before another GS iteration is performed. When a transfer is made to a coarser level, \( \bar{e}_k \) is set equal to the norm of the residuals immediately after the transfer is made (before any GS iterations are performed). The value of \( \bar{e}_k \) is not changed immediately after a fine grid transfer because testing showed that this decreased program efficiency.

If \( e_k > \eta \bar{e}_k \) the convergence rate is slow. This indicates that the error is smooth and should be approximated on a coarser grid.

### 4.5 Program Outputs

After each Gauss Seidel iteration, the error and residuals of each grid point are written to a file. The error referred to in this thesis is obtained by subtracting the current values from the exact solution (4.9). Residuals are calculated from (4.10).

\[
\text{error} = u_{\text{exact}} - u \tag{4.9}
\]
\[
\text{residuals} = Au - f \tag{4.10}
\]

### 4.6 Program Efficiency

This program can solve equations much more efficiently than a solver which uses standard Gauss Seidel iterative methods. Table 4.2 shows the number of iterations required by the program outlined above and a Gauss Seidel program to reach the indicated convergence. The number of iterations required for the multigrid program are weighted to account for iterations on different grid levels. The number indicated is the equivalent number of finest level iterations. A single iteration on level \( k \) requires the same amount of work as \( 2^{-(m-k)} \) iterations on level \( m \) (the finest level, here level 6). The Gauss Seidel program is executed on grid level 6 and begins with an initial guess of \( u = 0 \). Convergence is reached when the residual norm (4.6) is less than or equal to the convergence criteria.
<table>
<thead>
<tr>
<th>Problem</th>
<th>Gauss Seidel Iterations</th>
<th>Multigrid Iterations</th>
<th>Convergence Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2522</td>
<td>16.06</td>
<td>1.0E-06</td>
</tr>
<tr>
<td>2</td>
<td>1519</td>
<td>12.38</td>
<td>1.0E-06</td>
</tr>
<tr>
<td>3</td>
<td>5925</td>
<td>16.94</td>
<td>1.0E-07</td>
</tr>
<tr>
<td>4</td>
<td>1756</td>
<td>12.81</td>
<td>1.0E-06</td>
</tr>
<tr>
<td>5</td>
<td>2456</td>
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<td>5.0E-08</td>
</tr>
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<td>6</td>
<td>4351</td>
<td>15.69</td>
<td>5.0E-07</td>
</tr>
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<td>2748</td>
<td>15.56</td>
<td>7.0E-06</td>
</tr>
<tr>
<td>8</td>
<td>2666</td>
<td>14.94</td>
<td>5.0E-07</td>
</tr>
<tr>
<td>9</td>
<td>1509</td>
<td>13.00</td>
<td>1.0E-06</td>
</tr>
</tbody>
</table>

Table 4.2: Number of iterations required for convergence.
Chapter 5

Correction Method

5.1 Description of Correction

The proposed correction improves efficiency by adjusting the values of grid points where large residual spikes occur. The adjustments are made immediately after prolongation of the approximate solution when moving to a finer level. After the new fine level solution is obtained the residuals are calculated. The value of the point at the location of the absolute maximum residual is changed. The new value is obtained from the discretized equation (5.1), where $u_i$ is the point that is corrected:

$$u_i = \frac{1}{a_{ii}} \left[ f_i - \sum_{j=1}^{i-1} a_{ij}u_j - \sum_{j=i+1}^{M} a_{ij}u_j \right] \quad \text{for } i = 1 \text{ to } M \quad (5.1)$$

Only the spike which corresponds to the maximum residual is corrected. This can effectively increase accuracy and requires a minimal amount of additional work. This type of correction works well when moving to a fine level because the error is typically not smooth after prolongation.

This method is effective in reducing error because residual spikes correspond to error spikes. Figure 5.1 shows the plots of corresponding residual and error curves (Problem 5, Iteration 14). The largest residual is at point five, Figure 5.2 shows the error plot after this point has been replaced.

The new value of point 5 is more accurate than the original. After one GS iteration the effect of the correction is still apparent (Figure 5.3).

When implemented at appropriate times this correction method can reduce the error of the solution and reduce the number of iterations required to achieve residual convergence. The code used for the correction is in Appendix A.2. This code was inserted into the multigrid program code.
Figure 5.1: Problem 5, Iteration 14. Residual vs. Grid Point (left) and Error vs. Grid Point (right).

Figure 5.2: Problem 5, Iteration 14. Error vs. Grid Point after replacement of point 5.

Figure 5.3: Error vs. Grid Point one GS iteration later without (left) and with (right) correction.
5.2 Correction Processing Time

The amount of time required to perform a single correction was compared to the amount of time required to perform a single Gauss Seidel iteration. If residuals are calculated for all grid points, one correction takes approximately the same amount of time to implement as one Gauss Seidel iteration on the same level. Table 5.1 shows the amount of work required for a correction as a fraction of a Gauss Seidel iteration.

One correction requires the calculation of residuals, a comparison of the residuals (to determine the maximum residual), and the calculation of the new value of the corrected point. Two programs were written to compare the processing time of a Gauss Seidel iteration to a correction, see Appendix B. Each program was run four times, each time with a different number of grid point values. The level number which these corresponded to is shown in Table 5.1.

The running time required for each program was recorded and is presented in Table 5.1. In the table, 'GS Time' is the running time of the Gauss Seidel program. The correction program determines the max residual (includes the calculation of residuals and a comparison of the residuals). This running time is 'Max Residual Time' in Table 5.1. 'Residual/GS' is the ratio of 'Max Residual Time' to 'GS Time'. 'New Value Calculation' accounts for the calculation of the new value of the corrected point. The amount of work required for the calculation of the new value is equal to a fraction of a Gauss Seidel iteration, $1/n_k$ ($n_k$ is the number of grid points on level $k$). 'Total Correction/GS' is the sum of Residual/GS and New Value Calculation, it is the amount of work required for a correction expressed as a fraction of a Gauss Seidel iteration.

<table>
<thead>
<tr>
<th>Level</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS Time (s)</td>
<td>10.77</td>
<td>18.99</td>
<td>35.03</td>
<td>67.21</td>
</tr>
<tr>
<td>Max Residual Time (s)</td>
<td>8.54</td>
<td>16.01</td>
<td>32.02</td>
<td>60.76</td>
</tr>
<tr>
<td>Residual/GS</td>
<td>0.79</td>
<td>0.84</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>Calculation of New Value</td>
<td>0.143</td>
<td>0.067</td>
<td>0.032</td>
<td>0.016</td>
</tr>
<tr>
<td>Total Correction/GS</td>
<td>0.935</td>
<td>0.910</td>
<td>0.946</td>
<td>0.920</td>
</tr>
</tbody>
</table>

Table 5.1: Work required for a correction compared to a Gauss Seidel iteration.

Table 5.1 indicates that a single correction requires approximately the same amount of work as one Gauss Seidel iteration on the same level. This means that a correction performed on level 3 will increase the total amount of work required to solve a problem by only 0.125 equivalent level 6 GS iterations. Between 12 and 21 equivalent level 6 GS iterations were required for the solution of each problem (Table 4.2). Thus, a level 3 correction would increase computational work by 1% or less.
Chapter 6

Problems

The correction was tested on the nine problems shown in Table 6.1 below. All are second order differential equations with Dirichlet boundary conditions.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Equation</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-2u'' + 3u' + 6u = 6x^5 + 27x^4 + 14x^3 - 15x^2 - 66x + 35)</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>2</td>
<td>(u'' - 4u' + 2u = 2x^5 - 16x^4 - 22x^3 + 86x^2 - 36x - 2)</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>3</td>
<td>(u'' + 2u' + 3u = 2\sin x + 2\cos x)</td>
<td>elliptic</td>
</tr>
<tr>
<td>4</td>
<td>(u'' - 3u + u = -8\sin 3x - 9\cos 3x)</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>5</td>
<td>(u'' + 5u' - u = -3x^2 + 23x + 45)</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>6</td>
<td>(2u'' - 2u' + 3u = 3x^3 - 3x^2 + 2x + 38)</td>
<td>elliptic</td>
</tr>
<tr>
<td>7</td>
<td>(5u'' + 4u' + 5u = -12x^2 \sin x + 30 \cos x - 60x \sin x + 24x \cos x)</td>
<td>elliptic</td>
</tr>
<tr>
<td>8</td>
<td>(u'' + 5u' + 2u = 24e^x - 8e^x)</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>9</td>
<td>(u'' + 2u' - 3u = -12x^4 + 50x^3 + 15x^2 - 64x + 23)</td>
<td>hyperbolic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
<th>Domain</th>
<th>Lower BC</th>
<th>Upper BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(u = x^5 + 2x^4 + 5x^3 - 2x^2 + x + 4)</td>
<td>(0 - 1.0)</td>
<td>4.0</td>
<td>11.0</td>
</tr>
<tr>
<td>2</td>
<td>(u = x^5 + 2x^4 - 5x^3 + x^2 + x)</td>
<td>(0 - 1.0)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>(u = \sin x)</td>
<td>(0 - \pi/2)</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>(u = \sin 3x)</td>
<td>(0 - \pi/2)</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>(u = 3x^2 + 7x - 4)</td>
<td>(0 - 1.0)</td>
<td>-4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>6</td>
<td>(u = x^3 + x^2 - 2x + 10)</td>
<td>(0 - 1.0)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>7</td>
<td>(u = 3x^2 \cos x)</td>
<td>(0 - \pi/2)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>(u = 3e^x + 4e^{-x})</td>
<td>(0 - 1.0)</td>
<td>7.0</td>
<td>9.6</td>
</tr>
<tr>
<td>9</td>
<td>(u = 4x^4 - 6x^3 - x^2 + 8x - 3)</td>
<td>(0 - 1.0)</td>
<td>-3.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 6.1: Problems

The problems were discretized using three point central differencing (6.1), (6.2). The domain of each problem was split into 64 elements of equal size \(h\), yielding a computational domain of \(n = 63\) grid points. Six grid levels \((m = 6)\) were used in multigrid.
computations (refer to (4.5)).

\[
\frac{du}{dx}\bigg|_i = \frac{1}{2h} (u_{i+1} - u_{i-1}) \quad (6.1)
\]

\[
\frac{d^2 u}{dx^2}\bigg|_i = \frac{1}{h^2} (u_{i-1} - 2u_i + u_{i+1}) \quad (6.2)
\]
Chapter 7

Methods

To test the effectiveness of the correction, each problem was run several times. These runs are referred to as trials. The effects of the correction on solution accuracy and the number of iterations required for convergence were measured. The correction was implemented up to three times per trial.

As stated in Chapter 5, corrections were made immediately after prolongation when moving to a finer grid level. In addition corrections were only made after a Gauss Seidel iteration had been performed on each level. The correction is not effective when applied to the initial iterations in a problem because the error at each grid point is high. It is most effective when there is a large amount of localized error.

A trial was performed for each correction possible based on the above criteria (indicated in yellow in Figure 7.1). Some additional test runs with multiple corrections per run were also performed.

The accommodative algorithm did not control the flow of the correction trials. Instead the structure of the multigrid runs without corrections (labeled trial 0) was preserved in each of the correction trials. The structure of the runs can have a significant impact on the solution, and any variance can make it difficult to evaluate the effects of the correction. While the flow, or pattern, of the runs was preserved, the number of iterations on each level was varied in accordance with changes in the residual norm.

A generic structure is shown in Figure 7.1. It represents the basic flow that the accommodative algorithm used in this study produced. The structure of each of the trials performed in this study was a variation of that shown in Figure 7.1, with a varying number of iterations performed on each of the points in the figure. Points at which a correction could be applied are colored yellow. Plots of iteration vs. grid level for each multigrid run without corrections (trial 0 for each problem) are presented in Appendix C. From the plot of Problem 1, Trial 0 it can be seen that the trial began on level 1, then moved up with one Gauss Seidel iteration performed on levels 2, 3, and 4 and two GS iterations performed on level 5 and level 6, and so on.

The effects of the correction were measured in terms of the number of iterations
required and the accuracy of the solution. In Chapter 8 percent change in error and percent change in iterations are referred to. These are the change in number of iterations and the change in error with respect to the trial without corrections (trial 0).

\[
%\Delta Error = \frac{|error| - |error_{trial0}|}{|error_{trial0}|} \times 100 \quad (7.1)
\]

\[
%\Delta Iterations = \frac{iterations - iterations_{trial0}}{iterations_{trial0}} \times 100 \quad (7.2)
\]

Increased solution accuracy is indicated by a negative change in error. Similarly, a negative change in iterations indicates a decrease in the number of iterations required for convergence.

Figure 7.1: Generic multigrid structure.
Chapter 8

Results and Discussion

Several variables influenced the effectiveness of the correction. These included the nature of the corrected error spike, the grid level that the correction was implemented on, the time it was implemented, and the grid point that was corrected. Error was decreased in 68% of trials with one correction. The majority of the results summarized below are of trials with one correction only. The results of multiple correction trials are discussed only in section 8.7. Specific results of each trial are presented in Appendix E.

8.1 Error Spike Direction

The direction of the error spike that was corrected had a significant effect on whether the correction increased or decreased the error of the final solution. If the error of the corrected point was greater than the error of the two points adjacent to it, correcting it generally decreased the error of the solution (Figure 8.1). In this document, this is referred to as a “correct direction” spike because in the graphical view, the error spike appears to be “pointing” in the desirable direction. In some cases the error of the corrected point was negative and the error of the two surrounding points was positive, or vice versa. This situation is labeled “partially correct” and is shown in Figure 8.2. Corrections on partially correct spikes were not as effective as those made on correct spikes.

In the case of an “incorrect” direction spike, the error of the corrected point is smaller than the error of the adjacent points. Correcting an incorrect direction spike does not always yield positive results because the correction increases the error of the corrected point. Figures 8.1 and 8.2 show examples of error spikes in the “correct”, “partially correct”, and “incorrect” directions, as defined in this paper. Overall 58% of all spikes were in the correct direction, 28% in the incorrect direction, and 14% of spikes were partially in the correct direction.

Tables 8.1 and 8.2 show the effect of the direction of the corrected spike on the final
error for trials with a single correction. Corrections applied to spikes in the correct direction produced a decrease in solution error 86% of the time. In the trials in which corrections of correct direction spikes increased the solution error, it was increased an average of only 0.8%. Corrections made on spikes in the incorrect and partially correct directions caused an increase in solution error the majority of the time.

Figure 8.1: Error vs. Grid Point, “Correct” spike (left) and “Incorrect” spike (right).

Figure 8.2: Error vs. Grid Point, “Partially Correct” spike.

It is difficult to determine if an error spike is in the correct, partially correct, or incorrect direction when the exact solution is not known. The difficulty lies in determining whether the error of the points adjacent to the spike have a positive or negative margin. The direction of the spike (pointing up or down in the plot) can be determined from the residuals. If the diagonal of the A matrix is a negative value, the residual spike and error spike will point in the same direction (residual and error calculated from (4.10) and (4.9)). If the diagonal of the A matrix is a positive value, the error spike will point in the opposite direction of the residual spike (Figure 8.3).
Table 8.1: Percentage of trials error was decreased or increased per error spike direction.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Decreased</th>
<th>Increased</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>86%</td>
<td>14%</td>
</tr>
<tr>
<td>Incorrect</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>Partially Correct</td>
<td>44%</td>
<td>56%</td>
</tr>
<tr>
<td>Overall</td>
<td>68%</td>
<td>32%</td>
</tr>
</tbody>
</table>

Table 8.2: Average percentage change in error per error spike direction.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Decreased</th>
<th>Increased</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>5.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Incorrect</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Partially Correct</td>
<td>16.7</td>
<td>17.1</td>
</tr>
<tr>
<td>Total</td>
<td>6.4</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Unfortunately, a method of determining whether the surrounding error has a negative or positive margin has not been devised. Without this information, knowledge of the direction of the spike is not useful.

8.2 Grid Level

Corrections on coarser grid levels proved to be more effective than corrections on finer grid levels. Coarse level corrections correct error on a larger scale than finer level corrections and therefore have a greater influence on the accuracy of the final solution. This is illustrated in Table 8.3 and Figure 8.6. Table 8.3 shows the average of the absolute value of the percentage change in final error for trials with a single correction on the specified grid level.

Figure 8.6 shows the change in error produced by each trial with a single correction and indicates which corrections yielded a decreased number of total iterations. Each data point is the result of one trial. The level that each correction was implemented on is indicated by the color of the data point.
Figure 8.3: Error plot (top) and residual plot (bottom) for Problem 1, Trial 1 (level 3).

<table>
<thead>
<tr>
<th>Level</th>
<th>Average</th>
<th>% Δ Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.3: Average change in error per grid level.
8.3 Point in Multigrid Cycle

The point in the multigrid cycle that a correction is made can also affect the accuracy of the solution. Corrections made earlier in the cycle have a greater impact on solution accuracy than those made later in the cycle. For example, if a problem requires 36 iterations for convergence, a correction made on the 15th iteration will generally have a greater effect on accuracy than a correction made on the 34th iteration. Corrections made near the end of the cycle produced smaller errors when error increased.

Table 8.4 and Figure 8.5 illustrate this. In the table and figure the location of the corrected iteration in the multigrid cycle is given as a percentage of the total number of iterations. Figure 8.5 shows the results of all of the single correction trials (in the same way that Figure 8.6 does). One data point shows the change in error produced by each trial.

In Table 8.4 the location of the correction in the cycle is reported in three segments. The first segment (20-60%) represents the first set of corrections made on any grid level as illustrated in Figure 8.4. The final set of corrections is made in the last segment (75-100%) (Fig. 8.4). If three sets of corrections were possible, the second set was made in the middle segment (60-75%) (Fig. 8.4). Problem 5 was the only problem in which corrections were made in the 60-75% range of the cycle (Fig. 8.5).

Figure 8.4: Generic multigrid structure, grid level vs. point in cycle.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-15.4</td>
<td>43.5</td>
<td>-0.3</td>
<td>—</td>
<td>-11.4</td>
<td>11.9</td>
</tr>
<tr>
<td>4</td>
<td>-13.9</td>
<td>8.6</td>
<td>-0.3</td>
<td>—</td>
<td>-3.0</td>
<td>9.5</td>
</tr>
<tr>
<td>5</td>
<td>-1.2</td>
<td>1.1</td>
<td>-5.6</td>
<td>—</td>
<td>-1.3</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>-5.8</td>
<td>0.8</td>
<td>-19.7</td>
<td>—</td>
<td>-0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>All</td>
<td>-9.08</td>
<td>13.51</td>
<td>-6.45</td>
<td>—</td>
<td>-3.95</td>
<td>5.57</td>
</tr>
</tbody>
</table>

Table 8.4: Average percentage change in error per location in multigrid cycle.

Figure 8.5: Change in error vs. point in multigrid cycle.
8.4 Grid Location

Corrections on points located in the center of the grid were more effective than corrections on points near the grid boundaries. In the following discussion grid point locations are expressed as a percentage of the computational domain of the problem. It should be noted that Dirichlet boundary conditions were used in all of the trials.

Corrections on points located in the center of the grid had a greater impact on solution accuracy than those performed within a distance of 10% (of the grid length) of the boundaries. Figure 8.6 shows the percentage change in solution error vs. the location of corrected point as a percentage of the length of the grid. The percentage change in error for all single correction trials is plotted in Figure 8.6. Each of the plotted points is the result of one trial. On finer grids errors near the edge of the grid are reduced by the boundary conditions, and corrections near the grid edges are not as effective. Corrections implemented in the center of the grid also decreased error more frequently than corrections near the boundary conditions (Table 8.5).

![Figure 8.6: Change in final error vs. correction location and level.](image)
<table>
<thead>
<tr>
<th>Distance from Boundary (% grid length)</th>
<th>Error of Final Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Decreased</td>
</tr>
<tr>
<td>0-10%</td>
<td>8</td>
</tr>
<tr>
<td>10-25%</td>
<td>12</td>
</tr>
<tr>
<td>25-50%</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 8.5: Number of trials in which final error was increased or decreased vs. correction location.

### 8.5 Residual Magnitude

There was no correlation between the size of the residual spike and the percentage change in final error. Figure 8.7 shows the change in the error of the solution as a function of the residual/norm (norm refers to the residual norm) of the corrected point.

### 8.6 Problems

The effect of single corrections on the error of each problem is shown in Figure 8.8. This plot is nearly identical to Figure 8.6. As in Figure 8.6, each data point is the result of one trial and the results of all trials with one correction are plotted. In Figure 8.8 the problem that was solved in each trial is indicated. The effect of the corrections on solution accuracy varied between problems. Most of the differences can largely be attributed to the factors discussed above (spike direction, location, and grid level). Corrections were most effective in problem 5.

The number of single correction trials in which corrections were made on correct, incorrect, and partially correct direction spikes is shown in Figure 8.9. In problem 6, 100% of the spikes corresponding to the maximum residual were in the correct direction. Problem 8 had the largest number of spikes in the incorrect direction. The number of trials performed varies between problems because of the variation in the structure of the runs (see Appendix C). A larger number of trials were performed on problem 5 because it has more iterations than any other problem and moves between the grid levels an additional time. Only seven trials were performed on problem 2 because iterations were performed on level 2 at two points in the cycle instead of three.
Figure 8.7: Change in final error vs. residual/residual norm.
Figure 8.8: Change in final error vs. correction location and problem.
Figure 8.9: Direction of error spikes per problem.
8.7 Multiple Corrections

The results presented in the previous sections are the results of trials with a single correction. Twenty-six trials with multiple corrections were performed, 21 with two corrections, and 5 with three corrections. Appendix D shows the results of these trials. The percent change in error (7.1) and the percent change in number of iterations (7.2) are reported. In some cases the number of iterations did not change and therefore the percent change in number of iterations does not show up in the plot.

The graphs show the effects of the multiple correction trials and the corresponding single correction trials (performed at the same points in the cycle). The iteration that a correction was implemented after is indicated in parentheses next to the trial number. The iterations indicated in the single correction trials are not always the same as the iterations indicated in the multiple correction trial. This is because some multiple correction trials resulted in a decreased number of iterations and a move to a higher level at an earlier iteration. The details of the trials can be found in Appendix E.

In 12 trials the change in error produced by the multiple correction trial was within 6% of the sum of the error changes produced by the corresponding single correction trials. Six trials produced an improvement in solution accuracy over the combination of the single corrections. In 23 of the 26 trials the change in number of iterations produced by the multiple correction trial was equal to the sum of the changes in number of iterations produced by the corresponding single correction trials.
Chapter 9

Conclusions

This study is an initial evaluation performed to assess the viability of the correction method. The results indicate that it has the capacity to improve solution accuracy and potentially increase solver efficiency for a problem solved with multigrid methods. The correction can also cause a decrease in solution accuracy if it applied at an improper time.

The most important factor in determining whether a correction will produce positive results is the direction of the corrected error spike. Almost all of the corrections performed on “correct direction” error spikes increased solution accuracy. Unfortunately it is difficult to determine whether or not the spike is in the “correct” direction. This would be possible if a method was devised to determine whether the error had a positive or negative margin.

There was also a correlation between the location of the correction on the grid and correction effectiveness. Error was decreased in 75% of single correction trials in which the corrected point was in the central portion of the grid.

In most cases implementation of the correction did not affect the number of iterations required for convergence. In these cases the amount of computational work was increased by an amount approximately equal to that required for one Gauss Seidel iteration. It is up to the end user to decide whether the accuracy improvements produced in these cases are worth this extra computation time.

Maximum efficiency is achieved when the correction is implemented on coarser grid levels. Corrections made on coarser grid levels have a greater effect on solution accuracy and require the computation of fewer residuals. The efficiency of a fine level correction could be improved by calculating the residuals of points located near the center of the grid only. Multiple corrections can be as efficient as single corrections, and can be used to further increase accuracy.

Due to the limited number of problems tested in this study, it is difficult to determine if specific types of problems are better suited to this correction method. Future studies
should examine a more diverse set of problems, including two and three dimensional problems.
Bibliography


Appendix A

Multigrid Program - Fortran 90 Code

A.1 Multigrid - main.for

program main
integer :: ai, aifine, aicoarse, halfai, aj
integer :: aicoarsea, alocation
integer :: ajcoarse1, aijfine1, ajfine2
integer :: v, size, digits
integer :: coarse, rn, divs
integer :: k, l, m, div2, aim, index, lenname
integer :: iteration ! iteration number
character(len=80) :: name
character(len=80) :: name2
character(len=80) :: name3
character(len=80) :: name4
character(len=80) :: name5
character(len=80) :: name6
character(len=10) :: iteration
character(len=80) :: name
character(len=10) :: chariteration
character(len=100) :: errorname
real :: error, convrate, scriptem, avgerror
real :: proresidual, resresidual
real :: n, p
real :: normf, sumgs, weight
real :: sumdiff
real :: bc1, bc2, bcplace, level1
real :: scripteinit
real :: xrange
real, dimension(:,,:), allocatable :: asizes
real, dimension(:,,:), allocatable :: a
real, dimension(:,,:), allocatable :: x
real, dimension(:,,:), allocatable :: f
real, dimension(:,,:), allocatable :: ffine
real, dimension(:,,:), allocatable :: fres
real, dimension(:,,:), allocatable :: master
real, dimension(:,,:), allocatable :: pro
real, dimension(:,,:), allocatable :: res
real, dimension(:,,:), allocatable :: e
real, dimension(:,,:), allocatable :: olde
real, dimension(:,,:), allocatable :: ebar
real, dimension(:,,:), allocatable :: scripte
real, dimension(:,,:), allocatable :: exactx
real, dimension(:,,:), allocatable :: residual
real, dimension(:,:), allocatable :: residual2
real, dimension(:,:), allocatable :: currentf
real, dimension(:,:), allocatable :: abserror
integer, dimension(:,:), allocatable :: smooth

! get user input

print*, 'What is the index file path?'
read*, indexfile
! connect to index file
open (16, file=indexfile, status="old")
! read from file
read (16, *) ai, name, name2, name5, level1, xrange, bc1, bc2
close (unit=16)
ai = ai + 2
print*, 'ai=', ai ! number of grid points
print*, 'name=', name
print*, 'name2=', name2
print*, 'name5=', name5
print*, 'level1=', level1
print*, 'xrange=', xrange
print*, 'bc1=', bc1
print*, 'bc2=', bc2

print*, 'Where do you want the output to be written?'
read*, name3
print*, 'Where do you want the error text files?'
read*, n4
n = 0.5
print*, 'What is the stopping criteria?'
read*, scriptem

div2 = 0
aim = ai - 1
do
  if (mod((aim) / 2) /= 0) exit
  aim = aim / 2
  div2 = div2 + 1
end do
m = div2 ! number of grid levels

! creates asizes vector
! column vector to hold sizes of A beginning with level 1
size = ai - 2
allocate (asizes(m, 1))
asizes(m, 1) = size
do i = m - 1, 1, -1
  size = (size + 1) / 2 - 1
  asizes(i, 1) = size
end do
aj = sum (asizes)
print*, asizes
allocate (a (ai - 2, aj))
allocate (f (ai - 2, m))
allocate (exactx (ai - 2, m))
read (2,'(<ai-2>(f15.7))')((a(i,j),j=1,ai-2),i=1,ai-2)
close(unit=2)

!connect to solution vector file
open (3,file= name2,status="old")
!read from file
read (3,'(f15.7)')(f(i,m),i=1,ai-2)
close(unit=3)

!connect to exact solution file
open (9,file= name5,status="old")
!read from file
read (9,'(f15.7)')(exactx(i,m),i=1,ai-2)
close(unit=9)

!initial values
allocate(x(ai,m))
!boundary conditions
x(1,1)=bc1
x(3,1)=bc2

!level 1 solution
x(2,1)=level1
!epsilon for each level
allocate(scripte(m,1))
scripte(m,1)=scriptem
divs=4
do i=2,m-1
scripte(i,1)=(xrange/divs)**2
if (scripte(i,1)<scriptem) then
  do j=i,m-1
    scripte(i,1)=scriptem
  end do
  exit
end if
divs=divs*2
end do
scripte(1,1)=100.0

l=m
k=1
aicoarse=ai
allocat=asizes(m,1)
ajcoarsel=1
allocate(master(ai,m))
allocate(pro(1,1)) !random size
allocate(res(1,1)) !random size
allocate(residual(1,1)) !random size
allocate(residual2(1,1)) !random size
allocate(currentf(1,1)) !random size
allocate(abserror(1,1)) !random size
allocate(e(m,1))
allocate(olde(m,1))
allocate(olde(m,1))
allocate(smooth(m,1))
allocate(fine(ai-2,1))
sMOOTH=0

E=0
coarse=0
olde=1
iteration=0
ebar=100000

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rn=0
digits=1
p=2

open (4,file=name3,status="replace")
write (4,*),convergence criteria=',scripte(m,1)
write (4,*),initial epsilon=',scripte(2:m-1,1)
close (unit=4)

lennname=len(trim(name3))-4
print*,lennname,'=lenname
name8=name3:(lennname)//'2.txt'
open (8,file=name8,status="replace")
write(8,*),'Iteration Level Error'
close(unit=8)

!initial f and a matrices
ffine(2:aicoarse-3,1)=f(2:aicoarse-3,3)
ffine(1,1)=f(1,1)+bc1*a(2,ajcoarse)
ffine(aicoarse-2,1)=f(aicoarse-2,3)+bc2*a(aicoarse-3,alocation)
do j=m-1,2,-1
k=j
aifine=aicoarse
aicoarse=(aifine+1)/2
aicoarse=aicoarse-2
deadlocate(res)
deadlocate(pro)
alocate(res(aicoarse,aifine))
alocate(pro(aifine,aicoarse))
call prores(aifine,aicoarse,pro,res)
f(1:aicoarse,j)=matmul(res(2:aicoarse-2,aifine),
 & ffine(1:aifine-2,1))
ffine(1:aicoarse,1)=f(1,aicoarse,1)
alocation=sum(asizes(k:m,1))
ajcoarse1=1+allocation-(aicoarse-2)
ajfine1=allocation-(aicoarse-2)-(aifine-2)+1
ajfine2=allocation-(aicoarse-2)
a(1:aicoarse-2,ajcoarse1:allocation)=
 & matmul(matmul(res(2:aicoarse-2,aifine-1),
 & a(1:aifine-2,ajfines,ajfines2)),pro(2:aifine-1,2:aicoarse-1))
!aicoarse=matmul(matmul(res,aifine),pro)
f(1,j)=ffine(1,1)-bc1*a(2,ajcoarse)
f(aicoarse,j)=ffine(aicoarse,1)-bc2*a(aicoarse-1,allocation)
exactx(1:aicoarse,j)=matmul(res(2:aicoarse-1,2:aifine,1),
 & exactx(1,aifine-2,j+1))
endo
\[ a_{\text{aifine}} = a_{\text{aicoarse}} \]
\[ a_{\text{aicoarse}} = \frac{(a_{\text{aifine}} + l)}{2} \]
\[ a_{\text{aicoarse}} = a_{\text{aicoarse}} - 2 \]

\[
\text{print*}, \text{'}a_{\text{aifine}}=' , a_{\text{aifine}} \\
\text{print*}, \text{'}a_{\text{aicoarse}}=' , a_{\text{aicoarse}}
\]

\[
\text{open (4, file = name3, position = "append")} \\
\text{write (4, *) 'grid level=', k} \\
\text{close (unit=4)}
\]

\[
\text{open (4, file = name3, position = "append")} \\
\text{write (4, *) 'iteration=', iteration} \\
\text{write (4, *) ' '}
\]

\[
\text{close (unit=4)}
\]

\[
\text{open (5, file = name8, position = "append")} \\
\text{write (5, ' (i9)', advance = "no") 'iteration'} \\
\text{write (5, ' (i5)') k} \\
\text{write (5, *) ' '}
\]

\[
\text{close (unit=5)}
\]

\[
go \text{ to 2}
\]

---

! Presmoothing using Gauss Seidel

\[
1 \text{ open (4, file = name3, position = "append")} \\
\text{write (4, *) 'grid level=', k} \\
\text{close (unit=4)}
\]

\[
\text{call gs2(a, allocation, x, f, aicoarse, error, k, ai, aj,} \\
\& m, name3, n4, iteration, exactx, aicoarse, digits, avgerror)
\]

\[
\text{open (4, file = name3, position = "append")} \\
\text{if (rn == 1) then} \\
\text{write (4, *) 'prev residual norm=', resresidual} \\
\text{end if} \\
\text{if (rn == 2) then} \\
\text{write (4, *) 'pro prev residual norm=', proresidual} \\
\text{end if} \\
\text{write (4, *) 'residual norm=', error} \\
\text{conrate = error/olde(k,1)} \\
\text{write (4, *) 'convergence rate=', conrate} \\
\text{write (4, *) ' '}
\]

\[
\text{close (unit=4)}
\]

\[
4 \text{ open (5, file = name8, position = "append")} \\
\text{write (5, ' (i9)', advance = "no") 'iteration'} \\
\text{write (5, ' (i5)') k} \\
\text{write (5, ' (esll 2)') 'error'} \\
\text{write (5, *) ' '}
\]

\[
\text{close (unit=5)}
\]

\[
e(k,1) = \text{error} \\
\text{olde(k,1) = error}
\]

\[
\text{smooth(k,1) = \text{smooth(k,1)} + 1} \\
2 \text{ rn} = 0
\]

\[
\text{if (e(k,1) <= scripte(k,1)) then} \\
! \text{ print*, 'I'}
\]
if (k==l) then
!
| go to 3
else ! switch to finer level

rn=2
deallocate(pro)
deallocate(res)
allocate(pro(aifine,aicoarse))
allocate(res(aicoarse,aifine))
call prores(aifine,aicoarse,pro,res)

x(1:aifine,k+l)= master(1:aifine,k+l) + matmul
& (pro(1:aifine,1:aicoarse),(x(1:aicoarse,k)-matmul
& (res(1:aicoarse,1:aifine),master(1:aifine,k+l))))

xfine= xfineold + matmul(pro,(xcoarse-matmul(res,xfineold)))

if (k==l-l) then ! if at second highest level
    aicoarse=aifine
else
    aicoarse=aifine
    aifine=(aicoarse*2)-1
end if

k=k+1
allocation=sum(asizes(k:m,1))
aicoarse=aicoarse-2

calculate residuals of current solution
deallocate(residual)
deallocate(residual2)
deallocate(currentf)
allocate(residual(aicoarse,1))
allocate(residual2(aicoarse,1))
allocate(currentf(aicoarse,1))
currentf(1:aicoarse,1)=
    & matmul(a(1:aicoarse,1+allocation-aicoarse:allocation),
    & x(2:aicoarse-1,k))
do i=1,aicoarse
residual(i,1)=currentf(i,1)-f(1,k)
end do

write(chariteration,"(1<digits>)")iteration
erroname=trim(n4)//"rn"//trim(chariteration)//".txt"
open (12,file= erroname,status="replace")
do i=1,aicoarse
write(12,*),residual(i,1)
end do
close(unit=12)

! compute norm of residuals
do i=1,aicoarse
residual2(i,1)=(residual(i,1))**2
end do
proresidual=((sum(residual2))**.5)/aicoarse

******************************************************************************
! If Using Correction, Insert Correction Code Here
******************************************************************************

!Calculate Absolute Error of current solution
deallocate(abserror)
allocation(abserror(aicoarse,1))

do i=1,aicoarse
abserror(i,1)=exactx(i,k)-x(i+1,k)
end do

write(chariteration,"(I<digits>)")iteration
errorname=trim(n4)//"n"//trim(chariteration)//".txt"
open (15, file= errorname, status="replace")
do i=1,aicoarse
write(15,*) abserror(i,1)
end do
close(unit=15)

!back to GS!
cycle
goto 1
end if

else if (e(k,1)<=(n*ebar(k,D) .or. k==1) then
  ebar(k,1)=e(k,1)
go to 1
end if

!if at crudest level
if (k==2) then
!save values of current level
master(1:aicoarse,k)=x(1:aicoarse,k)
goto 1
end if

!save values of current level
master(1:aicoarse,k)=x(1:aicoarse,k)

!switch to a coarser level
rn=1
coarse=coarse+1
k=k-1
allocation=sum(asizes(k:m,1))
if (k==(m-1)) then !if you have moved to the second highest level
  aicoarse=(aifine+1)/2
else
  aifine=aicoarse
  aicoarse=(aifine+1)/2
end if

dallocate(pro)
dallocate(res)
allocation(pro(aifine,aicoarse))
allocation(res(aicoarse,aifine))
call prores(aifine,aicoarse,pro,res)
x(1:aicoarse,k)=
  & matmul(res(1:aicoarse,1:aifine),x(1:aifine,k+1))
!xcoarse=matmul(res,xfine)

ajcoarse1=1+allocation-(aicoarse-2)
ajfine1=allocation-(aicoarse-2)-(aifine-2)+1
ajfine2=allocation-(aicoarse-2)

! a(1:aicoarse-2,ajcoarse1:allocation)=
  &! matmul(matmul(res(2:aicoarse-1,2:aifine-1),
  & a(1:aifine-2,ajfine1:ajfine2)),pro(2:aifine-1,2:aicoarse-1))
!acoarse=matmul(matmul(res,ajfine),pro)

f(1:aicoarse-2,2)=matmul(a(1:aicoarse-2,ajcoarse1:allocation),
  & x(2:aicoarse-1,k)) + matmul(res(2:aicoarse-1,2:aifine-1),
  & (f(1:aifine-2,ajfine1:ajfine2),pro(2:aifine-1,2:aicoarse-1))
!fcoarse=matmul(acoarse,xcoarse) + matmul(res,ffine-matmul(ajfine,xfine))

if (0.7*scriptem>.2*e(k+1,1)) then
  scripte(k,1)=.7*scriptem
else
  scripte(k,1)=.2*e(k+1,1)
end if

!calculate residuals of current solution
dallocate(residual)
dallocate(residual2)
dallocate(currentf)
allocation(residual(aicoarse,1))
allocation(residual2(aicoarse,1))
allocation(currentf(aicoarse,1))
currentf(1:aicoarse,1)=
  & matmul(a(1:aicoarse,1+allocation-aicoarse:aallocation),
  & x(2:aicoarse-1,k))
do i=1,aicoarse
  residual(i,1)=currentf(i,1)-f(i,k)
end do
write(chariteration,"(1d10)")iteration
errorname=trim(n4)//"rn"/trim(chariteration)//".txt"
open (13,file= errorname,status="replace")
do i=1,aicoarse
  write(13,*),residual(i,1)
end do
close(unit=13)
! Compute norm of residuals
do i=1,aicoarse
residual2(i,1)=(residual(i,1))**2
end do
resresidual=((sum(residual2))**.5)/aicoarse

! Calculate Absolute Error of current solution
deallocate(abserror)
allocate(abserror(aicoarse,1))
do i=1,aicoarse
abserror(i,1)=exactx(i,k)-x(i+1,k)
end do
write(chariteration,"(I<digits>)")iteration
eerrorname=trim(n4)/*n*/trim(chariteration)/*.txt"
open (14,file= eerrorname,status="replace")
do i=1,aicoarse
write(14,*)abserror(i,1)
end do
close(unit=14)
ebar(k,l)=resresidual
olde(k,l)=resresidual
goto 1

3 weight=1
do i=m,1,-1
sumgs = weight*smooth(i,1)+sumgs
weight=.25*weight
end do

! Print # iterations
open (4,file= name3,position="append")
write(4,*)'Number of coarse grid transfers=',coarse
write(4,*)'Number of GS smoothing operations per level asc. order'
write(4,'(I<1>(44))')((smooth(i,j),j=1,1),i=1,m)
write(4,*)'Sum of GS iterations=',sumgs
close(unit=4)
end program main

A.2 Correction

! This code is inserted into main.for in the specified location

! Enter iteration of correction
if ((iteration==39)) then !.or. (iteration==11) ) then
  &  !.or. (iteration==26) then
  maxres=maxloc(residual2(2:aicoarse))
maxres=maxres(1)+1
maxratio=abs(residual(maxres))/proresidual
if (maxratio>2) then
  open (4, file= name3, position= "append")
  write(4,*)'maxres=',maxres
  write(4,*)'maxratio=',maxratio
  write(4,*) '
  write(4,*)'
  close(unit=4)
  if (maxres==aicoarse) then
    x(maxres+1,k)=(f(maxres,k)-x(maxres,k))
    \[ k = a(2,1+aocation-aicoarse) \]
    \[ k /a(2,2+ aocation-aicoarse) \]
  else
    x(maxres+1,k)=(f(maxres,k)-x(maxres,k))
    \[ k = a(2,1+aocation-aicoarse)-x(maxres+2,k) \]
    \[ k = a(2,3+aocation-aicoarse) \]
    \[ k /a(2,2+ aocation-aicoarse) \]
  end if
end if
end if
end if

A.3 Gauss Seidel - gs.for

subroutine gs2(a,aocation, x,f,aicoarse,error,k,ai,aj,
 & m,name3,n4,iteration,exactx,aicoarse,digits,avgerror)

!declare variables
integer ::aicoarse, imres,factor
integer ::iter,c
integer,intent(out) ::digits
integer,intent(inout) ::iteration
integer,intent(in) ::aocation,ai,aj,m
integer,intent(in) ::k,aicoarse
real ::num, mxres
real,intent(out) ::error,avgerror
character(len=80) ::name
character(len=80) ::name2
character(len=80) ::name3
character(len=80) ::n4
character(len=10) ::chariteration
character(len=100) ::errorname
real,dimension(ai-2,aj) ::a
real,dimension(ai,m),intent(inout) :: x
real,dimension(aicoarse,1) ::xnew
real,dimension(ai-2,m) ::f
real,dimension(aicoarse,aicoarse+1) ::b
real,dimension(aicoarse,1) ::residuals
real,dimension(aicoarse,1) ::residuals2
real,dimension(aicoarse,1) ::currentsol
real,dimension(aicoarse,1) ::abserror
real,dimension(ai-2,m),intent(in) ::exactx

b=0
!define augmented matrix b
do i=1,aicoarsea
  do j=1,aicoarsea
    b(i,j)=a(i,j+allocation-aicoarsea)
  end do
end do

do i=1,aicoarsea
  b(i,aicoarsea+1)=f(i,k)
end do

!GS iterations
iteration=iteration+1

imxres=0
mxres=0

do i=1,aicoarsea
  num=b(i,aicoarsea+1)
  do j=1,aicoarsea
    num=num-x(j+1,k)*b(i,j)
  end do
  xnew(i,1)=(num+x(i+1,k)*b(i,1))/b(i,i)
x(i+1,k)=xnew(i,1)
end do

currentsol(1:aicoarsea,1)=matmul(b(1:aicoarsea,1:aicoarsea),
  & x(2:aicoarse-1,k))

do i=1,aicoarsea
  residuals(i,1)=(currentsol(i,1)-f(i,k))
  if(abs(residuals(i,1))>abs(mxres)) then
    mxres = residuals(i,1)
    imxres = i*2**(m-k)
  end if
end do

open (4,file= name3,position="append")
write (4,*)'iteration=',iteration
write (4,*)'max residual=', mxres,' at location=',imxres
close (unit=4)

!Exact solution

do i=1,aicoarsea
  abserror(i,1)=exactx(i,k)-x(i+1,k)
end do

!average of abserror
if (k==m) then
  avererror=sum(abserror)/aicoarsea
end if

if (iteration < 10) then
digits=1
else if (iteration <100) then
digits=2
else if (iteration<1000) then
digits=3
else if (iteration<10000) then
digits=4
end if
!write error text files
write(chariteration,"(I<digits>)")iteration
errorname=trim(m4)"r"/trim(chariteration)".txt"

open (7,file= errorname,status="replace")
do i=1,aicoarse
write(7,*),residuals(i,1)
end do
close(unit=7)

write(chariteration,"(I<digits>)")iteration
errorname=trim(m4)"r"/trim(chariteration)".txt"

open (8,file= errorname,status="replace")
do i=1,aicoarse
write(8,*),abserror(i,1)
end do
close(unit=8)

!compute norm of residuals
do i=1,aicoarse
residuals2(i,1)=(residuals(i,1))**2
end do

error=((sum(residuals2))**.5)/aicoarse

end subroutine gs2

A.4 Prolongation and Restriction Operators - prores.for

subroutine prores(aifine,aicoarse,pro,res)
!
variables
integer :: c
integer,intent(in) :: aifine
integer,intent(in) :: aicoarse
real,dimension(aifine,aicoarse),intent(out) :: pro
real,dimension(aicoarse,aifine),intent(out) :: res
!
define prolongation operator matrix
pro=0
pro(1,1)=1
!
odd rows
do i=3,aifine,2
pro(i,c)=1
end do
!
even rows
do i=2,aifine-1,2
pro(i,c)=.5
pro(i,c+1)=.5
end do
!
define restriction operator matrix
res = 0.5 * transpose(pro)
res(1,1) = 1
res(1,2) = 0
res(aicoarse, aifine) = 1
res(aicoarse, aifine-1) = 0

end subroutine prores
Appendix B

Efficiency Test Programs - Fortran 90 Code

B.1 Gauss Seidel Efficiency Test Program

```fortran
program gtest

real :: x
real :: f
real :: a1
real :: a2
real :: a3
real :: a4
real :: a5
real :: a6
real :: a7
real :: x2
real :: x3
real :: x4
real :: x5
real :: x6
real :: x7

f = 5.463667
a1 = 3.254534
a2 = 5.979375
a3 = -37.85091
a4 = 4.235096
a5 = -15.49078
a6 = 7.094582
a7 = 9.430092
a8 = 4.687798
a9 = 3.068973
a10 = -6.975475
a11 = 3.254534
a12 = 5.979375
a13 = -37.85091
a14 = 4.235096
a15 = -15.49078
a16 = 7.094582
a17 = 9.430292
```

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<table>
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<th>Value</th>
</tr>
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<tr>
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</tr>
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x3| 3.576876  |
x4| 6.875432  |
x5| -6.873684 |
x6| 14.596123 |
x7| 9.6612868 |
x8| -5.298981 |
x9| 4.459823  |
x10| 8.945722  |
x11| -4.864655 |
x12| -5.086549 |
x13| 3.579876  |
x14| 6.875432  |
x15| -6.273684 |
x16| 13.58612  |
x17| 9.661986  |
x18| -5.098981 |
do k=1,10
  call cpu_time(t1)
  do i=1,10000000
    x=(f-a2*x2-a3*x3-a4*x4-a5*x5-a6*x6-a7*x7-a8*x8-a9*x9
      & -a10*x10-a11*x11-a12*x12-a13*x13-a14*x14-a15*x15
      & -a16*x16-a17*x17-a18*x18-a19*x19-a20*x20-a21*x21
      & -a22*x22-a23*x23-a24*x24-a25*x25-a26*x26-a27*x27
      & -a28*x28-a29*x29-a30*x30-a31*x31-a32*x32-a33*x33
      & -a34*x34-a35*x35
    & -a36*x36-a37*x37-a38*x38-a39*x39-a40*x40-a41*x41
    & -a42*x42-a43*x43-a44*x44-a45*x45-a46*x46-a47*x47
    & -a48*x48-a49*x49-a50*x50-a51*x51-a52*x52-a53*x53
    & -a54*x54-a55*x55-a56*x56-a57*x57-a58*x58-a59*x59
    & -a60*x60-a61*x61-a62*x62-a63*x63)/a1
end do

call cpu_time(t2)
print *, 'time to process = ', (t2-t1)
end do

end program gtest

B.2 Correction Efficiency Test Program

program correctiontest
real :: x
real :: f
real :: a1
real :: a2
real :: a3
real :: a4
real :: a5
real :: a6
real :: a7
real :: x2
real :: x3
real :: x4
real :: x5
real :: x6
real :: x7

x1= -2.458456
f=  5.463667
a1=  3.254534
a2=  5.979375
a3= -37.85091
a4=  4.235096
a5= -15.49078
a6=  7.094582
a7=  9.430092
a8=  4.687798
a9=  3.068973
a10= -6.975475
a11=  3.254534
a12=  5.979375
a13= -37.85091
a14=  4.235096
a15= -15.49078
a16=  7.094582
a17=  9.432092
a18=  4.687798
a19=  6.045973
a20= -6.978475
a21=  3.254534
a22=  5.979375
a23= -3.550912
a24=  4.735056
a25= -15.49078

52
a26 = 7.094582
a27 = 9.430902
a28 = 4.687798
a29 = 5.045973
a30 = -6.978475
a31 = 2.656565
a32 = 7.484155
a33 = -2.342189
a34 = 4.235096
a35 = -15.49078
a36 = 8.094582
a37 = 9.430902
a38 = 4.687798
a39 = 2.068973
a40 = -6.975475
a41 = 3.555434
a42 = 5.979375
a43 = -37.87091
a44 = 4.235096
a45 = -15.49078
a46 = 7.094582
a47 = 9.430902
a48 = 4.687798
a49 = 6.045973
a50 = -6.978475
a51 = 3.254534
a52 = 5.979375
a53 = -3.550912
a54 = 4.735056
a55 = -15.49078
a56 = 7.094582
a57 = 9.430902
a58 = 5.687798
a59 = 5.045973
a60 = -6.978475
a61 = 2.555665
a62 = 3.484155
a63 = -2.347189

x2 = -9.086549
x3 = 3.576876
x4 = 6.875432
x5 = -6.875432
x6 = 14.586123
x7 = 9.661286
x8 = -5.299891
x9 = 4.459823
x10 = 8.945722
x11 = 4.864665
x12 = -5.086549
x13 = 3.579876
x14 = 6.875432
x15 = -6.275884
x16 = 13.586123
x17 = 9.661986
x18 = -5.098981
x19 = 4.459823
x20 = 6.935722
x21 = -4.896685
x22 = -5.026549
x23 = 3.579816
x24 = 8.875432
x25 = -6.273884
x26 = 13.586123
x27=  9.645986
x28= -3.098981
x29=  4.459523
x30=  6.934322
x31= -7.890655
x32=  1.5644651
x33=  2.5861816
x34=  6.875432
x35= -6.875984
x36=  14.586123
x37=  2.5612868
x38= -5.278981
x39=  4.459823
x40=  5.945722
x41= -4.884955
x42= -5.086549
x43=  3.879876
x44=  9.875432
x45= -6.283684
x46=  13.586121
x47=  9.661986
x48= -5.097981
x49=  4.459523
x50=  5.935722
x51= -4.896555
x52= -5.026549
x53=  4.579816
x54=  8.879432
x55= -6.273684
x56=  18.586121
x57=  9.645986
x58= -3.098981
x59=  4.459523
x60=  6.934322
x61=  7.890655
x62=  1.5644651
x63=  2.5861816

do k=1,10

call cpu_time(t1)
!
residual calculation

do i=1,100000000
!
x=f-a1*x1-a2*x2-a3*x3-a4*x4-a5*x5-a6*x6-a7*x7-a8*x8-a9*x9

 & -a10*x10-a11*x11-a12*x12-a13*x13-a14*x14-a15*x15
 & -a16*x16-a17*x17-a18*x18-a19*x19-a20*x20-a21*x21
 & -a22*x22-a23*x23-a24*x24-a25*x25-a26*x26-a27*x27
 & -a28*x28-a29*x29-a30*x30-a31*x31-a32*x32-a33*x33
 & -a34*x34-a35*x35
 & -a36*x36-a37*x37-a38*x38-a39*x39-a40*x40-a41*x41
 & -a42*x42-a43*x43-a44*x44-a45*x45-a46*x46-a47*x47
 & -a48*x48-a49*x49-a50*x50-a51*x51-a52*x52-a53*x53
 & -a54*x54-a55*x55-a56*x56-a57*x57-a58*x58-a59*x59
 & -a60*x60-a61*x61-a62*x62-a63*x63
end do
!
comparison

do j=1,98412698  !100000000*62/63  !62 comparisons are made for every 63 runs

if (x > 2) then
  x = 1
end if
end do

call cpu_time(t2)

print *, 'time to process = ', (t2 - t1)

end program correction test
Appendix C

Accomodative Algorithm Runs

![Graph showing iteration vs. level for Problem 1, Trial 0]
Appendix D

Multiple Correction Results
Appendix E

Trial Results

The tables below show the results of all of the trials executed for this study. The letter p indicates the problem number, t indicates the trial number. Trial 0 is the multigrid run performed without any corrections. The trials which are listed on multiple lines have multiple corrections, the net result of the trial is shown on the first line.

The 'Iteration' column indicates the Gauss Seidel iteration the correction was performed after. 'Point in Cycle' is the ratio of the iteration number to the total number of iterations multiplied by a factor of 100. 'Level' indicates the grid level that the correction was made on. 'Direction' refers to the error spike direction (see section 8.1). 'Grid Point' is the grid point which was corrected. 'Location' is the ratio of 'Grid Point' to the total number of grid points on the level multiplied by a factor of 100. 'Residual/Norm' is the ratio of value of the residual of the corrected point prior to the correction to the residual norm (4.6).

'Total Iterations' is the total number of iterations required for convergence (convergence criteria are given in Table 4.2. 'Weighted Iterations' is the equivalent number of level 6 iterations (see section 4.6). '% Δ Iterations' is the percentage change in number of iterations required for convergence (7.2). A negative value indicates a decrease in the total iterations.

'|Error|' is the average of the absolute value of the error of the solution. '% Δ Error' is the percentage difference in error between the trial and trial 0 (7.1). A negative value indicates an increase in accuracy.

'Δ Work' is obtained from subtracting the weighted iterations of the trial from the weighted iterations of trial 0 and adding the value of one iteration on the level of each correction (each correction takes approximately the same time to process as a Gauss Seidel iteration, section 5.2). A positive value indicates an increase in computational work. It should be noted that this is a calculated value and not an actual measure of computation time.
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<p>| Problem, Trial | Iteration | Point in Cycle (%) | Level | Direction | Grid Point | Location (%) span | Residual/Norm | Total Iterations | Weighted Iterations | % Δ Iterations | |Error| | Δ Error | Δ Work (iterations) |
|----------------|-----------|-------------------|------|-----------|------------|------------------|--------------|-----------------|---------------------|-----------------|----------|----------------|-------------|-------------------|
| p5t0           | -         | -                 | -    | -         | -          | -                | -            | 51              | 20.44               | -                | 5.01E-06 | -             | -           | -                 |
| p5t1           | 12        | 23.5              | 3    | Incorrect | 3          | 42.9             | 3.3          | 51              | 20.44               | 0.00             | 2.40E-06 | -24.05        | 0.13        | 0.13               |
| p5t2           | 14        | 27.5              | 4    | Correct   | 5          | 33.3             | 9.0          | 51              | 20.44               | 0.00             | 3.5E-06 | -30.25        | 0.25        | 0.25               |
| p5t3           | 16        | 31.4              | 5    | Incorrect | 13         | 41.9             | 13.0         | 51              | 20.44               | 0.00             | 4.86E-06 | -1.00         | 0.05        | 0.05               |
| p5t4           | 18        | 35.3              | 6    | Correct   | 30         | 47.6             | 19.1         | 51              | 20.44               | 0.00             | 3.80E-06 | -24.14        | 1.00        | 1.00               |
| p5t5           | 31        | 60.8              | 3    | Incorrect | 2          | 28.6             | 3.5          | 51              | 20.44               | 0.00             | 4.99E-06 | -0.26         | 0.13        | 0.13               |
| p5t6           | 32        | 62.7              | 4    | Correct   | 3          | 20.0             | 5.6          | 51              | 20.44               | 0.00             | 5.0E-06  | -0.27         | 0.25        | 0.25               |
| p5t7           | 34        | 68.0              | 5    | Incorrect | 4          | 12.9             | 10.4         | 50              | 19.44               | -5.14            | 4.7E-06  | -5.58         | -0.50       | -0.50              |
| p5t8           | 36        | 70.6              | 6    | Correct   | 35         | 55.6             | 18.4         | 51              | 20.44               | 0.00             | 4.02E-06 | -19.69        | 1.00        | 1.00               |
| p5t9           | 45        | 88.2              | 4    | Correct   | 2          | 13.3             | 7.5          | 51              | 20.44               | 0.00             | 4.80E-06 | -4.11         | 0.25        | 0.25               |
| p5t10          | 47        | 92.2              | 5    | Correct   | 2          | 6.5              | 12.2         | 51              | 20.44               | 0.00             | 4.94E-06 | -1.44         | 0.50        | 0.50               |
| p5t11          | 49        | 96.1              | 6    | Correct   | 3          | 4.8              | 22.0         | 51              | 20.44               | 0.00             | 5.03E-06 | 0.38          | 1.00        | 1.00               |
| p5t12          | 14        | 27.5              | 4    | Correct   | 5          | 33.3             | 9.0          | 51              | 20.44               | 0.00             | 4.2E-06  | -16.59        | 0.75        | 0.75               |
| p5t12          | 16        | 31.4              | 5    | Incorrect | 13         | 41.9             | 12.9         | 51              | 20.44               | 0.00             | 5.8E-06  | 15.65         | 1.25        | 1.25               |
| p5t13          | 14        | 27.5              | 4    | Correct   | 5          | 33.3             | 9.0          | 51              | 20.44               | 0.00             | 5.8E-06  | 15.65         | 1.25        | 1.25               |
| p5t14          | 18        | 35.3              | 6    | Correct   | 30         | 47.6             | 18.9         | 51              | 20.44               | 0.00             | 2.9E-06  | -41.35        | 0.75        | 0.75               |
| p5t15          | 14        | 27.5              | 4    | Correct   | 5          | 33.3             | 9.0          | 51              | 20.44               | 0.00             | 2.87E-06 | -42.75        | 1.25        | 1.25               |
| p5t15          | 34        | 66.7              | 5    | Correct   | 3          | 9.7              | 10.6         | 51              | 20.44               | 0.00             | 2.87E-06 | -42.75        | 1.25        | 1.25               |
| p5t15          | 47        | 92.2              | 5    | Correct   | 2          | 6.5              | 11.0         | 51              | 20.44               | 0.00             | 2.87E-06 | -42.75        | 1.25        | 1.25               |</p>
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