# **Chapter 1**

# Example problem: SUPG-stabilised solution of the 2D advection diffusion equation

In this example we discuss the SUPG-stabilised solution of the 2D advection-diffusion problem

### Two-dimensional advection-diffusion problem in a rectangular domain

Solve

Pe 
$$\sum_{i=1}^{2} w_i(x_1, x_2) \frac{\partial u}{\partial x_i} = \sum_{i=1}^{2} \frac{\partial^2 u}{\partial x_i^2} + f(x_1, x_2),$$
 (1)

in the rectangular domain  $D=\{(x_1,x_2)\in[0,1]\times[0,2]\}$ , with Dirichlet boundary conditions

$$u|_{\partial D} = u_0, \qquad (2)$$

where the *Peclet number*, Pe the boundary values,  $u_0$ , the source function  $f(x_1, x_2)$ , and the components of the "wind"  $w_i(x_1, x_2)$  (i = 1, 2) are given.

We set  $f(x_1,x_2)=0$  and assign the boundary conditions such that

$$u_0(x_1, x_2) = \tanh(1 - \alpha(x_1 \tan \Phi - x_2)),$$
 (3)

For large values of  $\alpha$ , this boundary data approaches a step, oriented at an angle  $\Phi$  against the  $x_1$ -axis.

In the computations we will impose the "wind"

$$\mathbf{w}(x_1, x_2) = \begin{pmatrix} \sin(6x_2) \\ \cos(6x_1) \end{pmatrix}, \qquad (4)$$

illustrated in this vector plot:

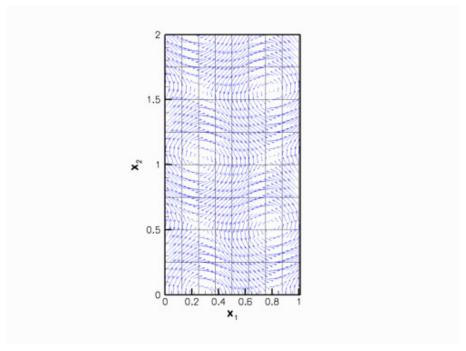


Figure 1.1 Plot of the wind.

The figures below show plots of the solution for  $\Phi=45^\circ,~\alpha=50$  and a Peclet number of Pe=200, with and without SUPG stabilisation. The wire-mesh plot shows the solution computed on a 10x10 mesh, the shaded surface represents the solution obtained from an unstabilised solution on a 150x150 mesh. Note how SUPG stabilisation "suppresses the wiggles" on the relatively coarse mesh.

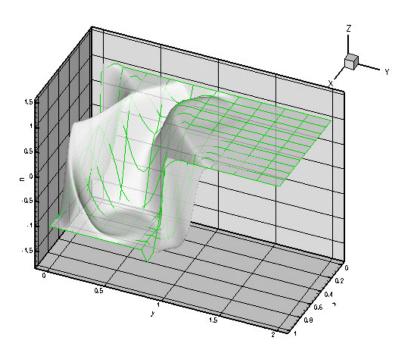


Figure 1.2 Plot of the SUPG-stabilised solution at different levels of mesh refinement.

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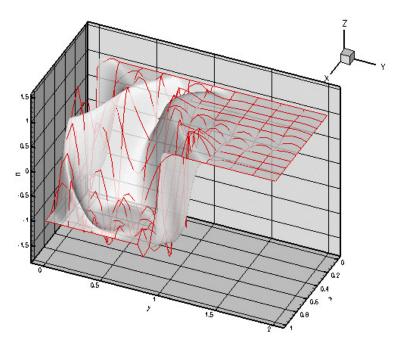


Figure 1.3 Plot of the unstabilised solution at different levels of mesh refinement.

### 1.1 The driver code

Overall, the structure of the driver code is very similar to that used for the problem without stabilisation.

### 1.1.1 To be written:

- · Discuss SUPG theory.
- · Implementation and the role of basis, shape and test functions (our equations are isoparametric)

Until we get around to completing this example, here's the driver code. Fairly self-explanatory, isn't it?

```
//LIC// This file forms part of oomph-lib, the object-oriented,
//LIC// multi-physics finite-element library, available
//LIC// at http://www.oomph-lib.org.
//LIC//
//LIC// Copyright (C) 2006-2023 Matthias Heil and Andrew Hazel
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//LIC// version 2.1 of the License, or (at your option) any later version.
//LTC//
//LIC// This library is distributed in the hope that it will be useful,
//LIC// but WITHOUT ANY WARRANTY; without even the implied warranty of
//LIC// MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU
//LIC// Lesser General Public License for more details.
//LIC//
//LIC// You should have received a copy of the GNU Lesser General Public //LIC// License along with this library; if not, write to the Free Software
//LIC// Foundation, Inc., 51 Franklin Street, Fifth Floor, Boston, MA
//LIC// 02110-1301 USA.
//LIC//
//LIC// The authors may be contacted at oomph-lib@maths.man.ac.uk.
//Driver for a simple 2D adv diff problem with SUPG stabilisation
//Generic routines
// The Poisson equations
#include "advection_diffusion.h"
// The mesh
```

```
#include "meshes/rectangular_quadmesh.h"
using namespace std;
using namespace oomph;
//=====start_of_namespace======
/// Namespace for global parameters: Unforced problem with
/// boundary values corresponding to a steep tanh step profile
/// oriented at 45 degrees across the domain.
namespace GlobalPhysicalParameters
 /// Peclet number
double Peclet=200.0;
 /// Parameter for steepness of step in boundary values
double Alpha=50.0;
 /// Parameter for angle of step in boundary values: 45 degrees
double TanPhi=1.0;
    Some "solution" for assignment of boundary values
 void get_boundary_values(const Vector<double>& x, Vector<double>& u)
 u[0] = tanh(1.0-Alpha*(TanPhi*x[0]-x[1]));
 /// Zero source function
 void source_function(const Vector<double>& x_vect, double& source)
  source=0.0;
 /// Wind
 void wind_function(const Vector<double>& x, Vector<double>& wind)
  wind[0]=sin(6.0*x[1]);
 wind[1]=\cos(6.0*x[0]);
} // end of namespace
//===== start_of_problem_class=======
/// 2D AdvectionDiffusion problem on rectangular domain, discretised
/// with refineable 2D QAdvectionDiffusion elements. The specific type
/// of element is specified via the template parameter.
template<class ELEMENT>
class SUPGAdvectionDiffusionProblem : public Problem
public:
 /// Constructor: Pass pointer to source and wind functions, and
 /// flag to indicate if stabilisation is to be used.
 SUPGAdvectionDiffusionProblem(
 AdvectionDiffusionEquations<2>::AdvectionDiffusionSourceFctPt source_fct_pt,
 {\tt AdvectionDiffusionEquations <2>:: AdvectionDiffusionWindFctPt wind\_fct\_pt,}
 const bool& use_stabilisation);
 /// Destructor. Empty
 ~SUPGAdvectionDiffusionProblem(){}
 /// Update the problem specs before solve: Reset boundary conditions
 /// to the values from the tanh solution and compute stabilisation
 /// parameter.
 void actions before newton solve();
 /// Update the problem after solve (empty)
 void actions_after_newton_solve(){}
 /// Doc the solution.
void doc solution();
 /// Overloaded version of the problem's access function to
 /// the mesh. Recasts the pointer to the base Mesh object to
 /// the actual mesh type.
 RectangularQuadMesh<ELEMENT>* mesh_pt()
```

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```
return dynamic_cast<RectangularQuadMesh<ELEMENT>*>(
   Problem::mesh_pt());
private:
 /// DocInfo object
 /// Pointer to source function
AdvectionDiffusionEquations<2>::AdvectionDiffusionSourceFctPt Source_fct_pt;
 /// Pointer to wind function
AdvectionDiffusionEquations<2>::AdvectionDiffusionWindFctPt Wind_fct_pt;
 /// Flag to indicate if stabilisation is to be used
bool Use stabilisation:
}; // end of problem class
//----start_of_constructor-----
/// Constructor for AdvectionDiffusion problem: Pass pointer to
/// source function and wind functions and flag to indicate
/// if stabilisation is to be used.
template<class ELEMENT>
SUPGAdvectionDiffusionProblem<ELEMENT>::SUPGAdvectionDiffusionProblem(
AdvectionDiffusionEquations<2>::AdvectionDiffusionSourceFctPt source_fct_pt,
AdvectionDiffusionEquations<2>::AdvectionDiffusionWindFctPt wind_fct_pt,
const bool& use_stabilisation)
 : Source_fct_pt(source_fct_pt), Wind_fct_pt(wind_fct_pt),
    Use_stabilisation(use_stabilisation)
 // Set output directory
 if (use_stabilisation)
   Doc_info.set_directory("RESLT_stabilised");
else
   Doc_info.set_directory("RESLT_unstabilised");
 // Setup mesh
 // # of elements in x-direction
unsigned n x=40:
 // # of elements in y-direction
unsigned n_y=40;
 // Domain length in x-direction
double 1 x=1.0;
 // Domain length in y-direction
double 1_y=2.0;
 // Build and assign mesh
Problem::mesh pt() =
 new RectangularQuadMesh<ELEMENT>(n_x,n_y,l_x,l_y);
 // Set the boundary conditions for this problem: All nodes are
 // free by default -- only need to pin the ones that have Dirichlet
 // conditions here
 unsigned num_bound = mesh_pt()->nboundary();
 for(unsigned ibound=0;ibound<num_bound;ibound++)</pre>
   unsigned num_nod= mesh_pt()->nboundary_node(ibound);
   for (unsigned inod=0;inod<num_nod;inod++)</pre>
     mesh_pt()->boundary_node_pt(ibound,inod)->pin(0);
    // end loop over boundaries
 // Complete the build of all elements so they are fully functional
 // Loop over the elements to set up element-specific
 // things that cannot be handled by the (argument-free!) ELEMENT // constructor: Pass pointer to source function
 unsigned n_element = mesh_pt()->nelement();
 for (unsigned i=0;i<n_element;i++)</pre>
   // Upcast from GeneralsedElement to the present element
```

```
ELEMENT *el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(i));
      //Set the source function pointer
     el_pt->source_fct_pt() = Source_fct_pt;
      //Set the wind function pointer
     el_pt->wind_fct_pt() = Wind_fct_pt;
      // Set the Peclet number
     el_pt->pe_pt() = &GlobalPhysicalParameters::Peclet;
 // Setup equation numbering scheme
cout «"Number of equations: " « assign_eqn_numbers() « std::endl;
} // end of constructor
//----start_of_actions_before_newton_solve---
/// Update the problem specs before solve: (Re-)set boundary conditions
template<class ELEMENT>
void SUPGAdvectionDiffusionProblem<ELEMENT>::actions_before_newton_solve()
  // How many boundaries are there?
 unsigned num_bound = mesh_pt()->nboundary();
  //Loop over the boundaries
  for(unsigned ibound=0;ibound<num_bound;ibound++)</pre>
   \{ \begin{tabular}{ll} \b
     unsigned num_nod=mesh_pt()->nboundary_node(ibound);
      // Loop over the nodes on boundary
      for (unsigned inod=0;inod<num_nod;inod++)</pre>
        {
          // Get pointer to node
         \label{eq:node_pt_mode_pt_inder} \begin{tabular}{ll} $\text{Node*} & $\text{nod\_pt=mesh\_pt}()$ ->boundary_node_pt(ibound,inod); \\ \end{tabular}
           // Extract nodal coordinates from node:
         Vector<double> x(2);
          x[0] = nod_pt -> x(0);
         x[1] = nod_pt -> x(1);
          // Get boundary value
          Vector<double> u(1);
         GlobalPhysicalParameters::get_boundary_values(x,u);
         // Assign the value to the one (and only) nodal value at this node nod_pt->set_value(0,u[0]);
    }
  // Now loop over all elements and set the stabilisation parameter
 unsigned n_element = mesh_pt()->nelement();
  for(unsigned i=0;i<n_element;i++)</pre>
    {
      // Upcast from GeneralsedElement to the present element
     ELEMENT *el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(i));
     // Use stabilisation?
     if (Use_stabilisation)
       {
          //Compute stabilisation parameter
          el_pt->compute_stabilisation_parameter();
     else
         //Compute stabilisation parameter
         el_pt->switch_off_stabilisation();
    }
} // end of actions before solve
/// Doc the solution
template<class ELEMENT>
void SUPGAdvectionDiffusionProblem<ELEMENT>::doc_solution()
 ofstream some file;
```

```
char filename[100];
// Number of plot points: npts x npts
unsigned npts=5;
 // Output solution
sprintf(filename, "%s/soln%i.dat", Doc_info.directory().c_str(),
        Doc_info.number());
some_file.open(filename);
mesh_pt()->output(some_file,npts);
some_file.close();
} // end of doc
/// Driver code for 2D AdvectionDiffusion problem
int main()
 //Set up the problem with stabilisation
 bool use_stabilisation=true;
  // Create the problem with 2D nine-node elements from the
  // QAdvectionDiffusionElement family. Pass pointer to
  // source and wind function.
 SUPGAdvectionDiffusionProblem<OSUPGAdvectionDiffusionElement<2.3> >
  problem(&GlobalPhysicalParameters::source_function,
          &GlobalPhysicalParameters::wind_function,
          use_stabilisation);
 // Solve the problem
 problem.newton_solve();
 //Output the solution
 problem.doc_solution();
 //Set up the problem without stabilisation
 bool use_stabilisation=false;
  // Create the problem with 2D nine-node elements from the
 // QAdvectionDiffusionElement family. Pass pointer to
  // source and wind function.
 SUPGAdvectionDiffusionProblem<QSUPGAdvectionDiffusionElement<2,3>>
  problem(&GlobalPhysicalParameters::source_function,
          &GlobalPhysicalParameters::wind_function,
          use_stabilisation);
 // Solve the problem
 problem.newton_solve();
  //Output the solution
 problem.doc_solution();
} // end of main
```

### 1.2 Source files for this tutorial

• The source files for this tutorial are located in the directory:

```
demo_drivers/advection_diffusion/two_d_adv_diff_SUPG/
```

· The driver code is:

 $\label{lem:condition} $$ demo\_drivers/advection\_diffusion/two\_d\_adv\_diff\_SUPG/two\_d\_adv\_diff\_\leftrightarrow SUPG.cc$ 

## 1.3 PDF file

A pdf version of this document is available.