Chapter 1

Example problem: Steady flow in a curved tube

The problem of steady flow in a curved tube is considered with a prescribed Poiseuille flow at the inlet and a traction-free outlet condition. It is not clear that the latter is appropriate, but the main aim of this example is to check that the `TubeMesh` works correctly.

A detailed comparison between the flow field and the Dean solution should be performed for validation purposes, but the qualitative features seem reasonable.

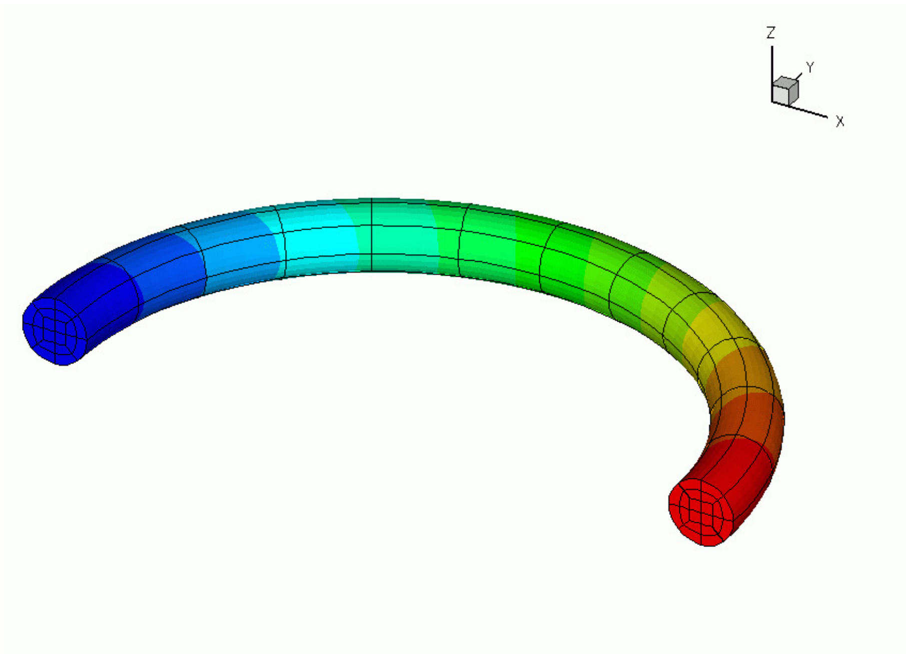

Figure 1.1 Sketch of the problem with pressure contours.

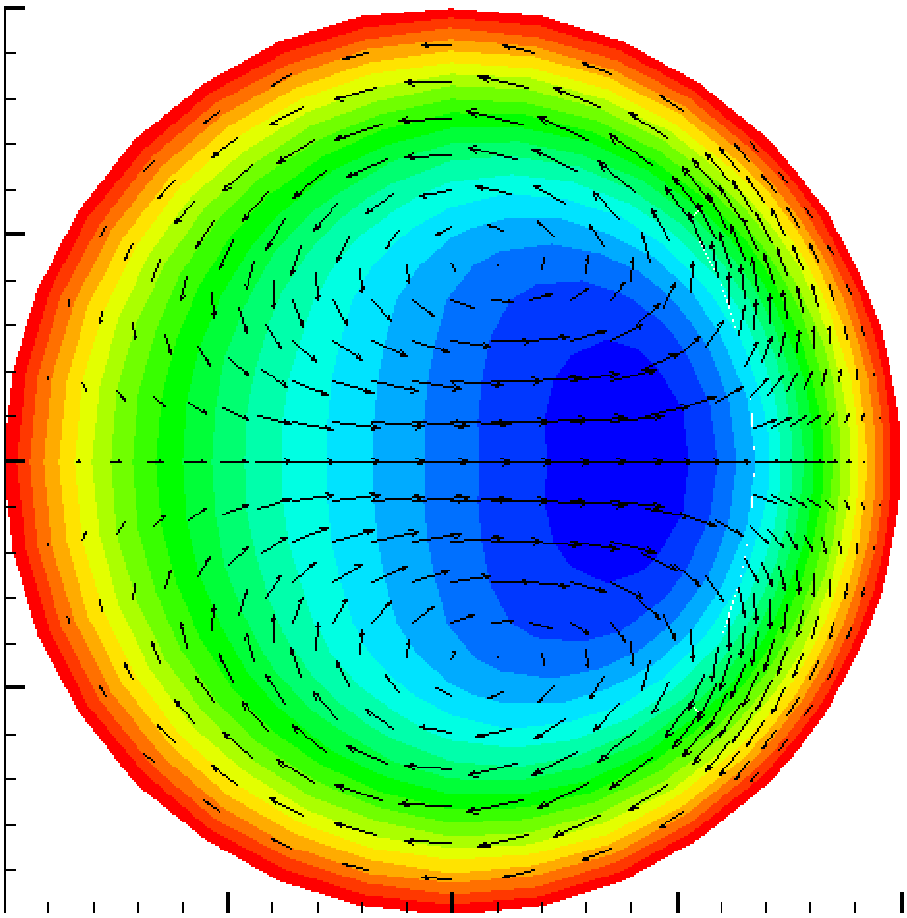

Figure 1.2 Contours of axial velocity and secondary streamlines.

Detailed documentation to be written. Here's the driver code...

```
//LIC// ====================================================================
//LIC// This file forms part of oomph-lib, the object-oriented,
//LIC// multi-physics finite-element library, available
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//LIC// The authors may be contacted at oomph-lib@maths.man.ac.uk.
//LIC//
//LIC//====================================================================
/// Driver for a 3D navier stokes steady entry flow problem in a
/// uniformly curved tube

//Generic routines
#include "generic.h"
#include "navier_stokes.h"

// The mesh
```

```
#include "meshes/tube_mesh.h"

using namespace std;

using namespace oomph;


//=start_of_MyCurvedCylinder===================================
//A geometric object that represents the geometry of the domain
//================================================================
class MyCurvedCylinder : public GeomObject
{
public:

 /// Constructor that takes the radius and curvature of the tube
 /// as its arguments
 MyCurvedCylinder(const double &radius, const double &delta) :
  GeomObject(3,3), Radius(radius), Delta(delta) { }

/// Destructor
virtual~MyCurvedCylinder(){}

/// Lagrangian coordinate xi
void position (const Vector<double>& xi, Vector<double>& r) const
{
 r[0] = (1.0/Delta)*cos(xi[0]) + xi[2]*Radius*cos(xi[0])*cos(xi[1]);
 r[1] = (1.0/Delta)*sin(xi[0]) + xi[2]*Radius*sin(xi[0])*cos(xi[1]);
 r[2] = -xi[2]*Radius*sin(xi[1]);
}


/// Return the position of the tube as a function of time
/// (doesn't move as a function of time)
void position(const unsigned& t,
              const Vector<double>& xi, Vector<double>& r) const
  {
   position(xi,r);
  }

private:

 /// Storage for the radius of the tube
 double Radius;

 //Storage for the curvature of the tube
 double Delta;
};

//=start_of_namespace================================================
/// Namespace for physical parameters
//===================================================================
namespace Global_Physical_Variables
{
 /// Reynolds number
 double Re=50;

 /// The desired curvature of the pipe
 double Delta=0.1;
} // end_of_namespace


//=start_of_problem_class=============================================
/// Entry flow problem in tapered tube domain
//====================================================================
template<class ELEMENT>
class SteadyCurvedTubeProblem : public Problem
{

public:

 /// Constructor: Pass DocInfo object and target errors
 SteadyCurvedTubeProblem(DocInfo& doc_info, const double& min_error_target,
                 const double& max_error_target);

 /// Destructor (empty)
 ~SteadyCurvedTubeProblem() {}

 /// Update the problem specs before solve
 void actions_before_newton_solve();

 /// After adaptation: Pin redudant pressure dofs.
 void actions_after_adapt()
  {
   // Pin redudant pressure dofs
   RefineableNavierStokesEquations<3>::
    pin_redundant_nodal_pressures(mesh_pt()->element_pt());
  }
```

```
 /// Doc the solution
 void doc_solution();

 /// Overload generic access function by one that returns
 /// a pointer to the specific  mesh
 RefineableTubeMesh<ELEMENT>* mesh_pt()
  {
   return dynamic_cast<RefineableTubeMesh<ELEMENT>*>(Problem::mesh_pt());
  }

private:

 /// Doc info object
 DocInfo Doc_info;

 /// Pointer to GeomObject that specifies the domain volume
 GeomObject *Volume_pt;

}; // end_of_problem_class




//=start_of_constructor===================================================
/// Constructor: Pass DocInfo object and error targets
//========================================================================
template<class ELEMENT>
SteadyCurvedTubeProblem<ELEMENT>::SteadyCurvedTubeProblem(DocInfo& doc_info,
                                              const double& min_error_target,
                                              const double& max_error_target)
 : Doc_info(doc_info)
{

 // Setup mesh:
 //------------

 // Create GeomObject that specifies the domain geometry
 //The radius of the tube is one and the curvature is specified by
 //the global variable Delta.
 Volume_pt=new MyCurvedCylinder(1.0,Global_Physical_Variables::Delta);
 //Define pi
 const double pi = MathematicalConstants::Pi;
 //Set the centerline coordinates spanning the mesh
 Vector<double> centreline_limits(2);
 centreline_limits[0] = 0.0;
 centreline_limits[1] = pi;

 //Set the positions of the angles that divide the outer ring
 //These must be in the range -pi,pi, ordered from smallest to
 //largest
 Vector<double> theta_positions(4);
 theta_positions[0] = -0.75*pi;
 theta_positions[1] = -0.25*pi;
 theta_positions[2] = 0.25*pi;
 theta_positions[3] = 0.75*pi;

 //Define the radial fraction of the central box (always halfway
 //along the radius)
 Vector<double> radial_frac(4,0.5);
 // Number of layers in the initial mesh
 unsigned nlayer=6;

 // Build and assign mesh
 Problem::mesh_pt()= new RefineableTubeMesh<ELEMENT>(Volume_pt,
                                                     centreline_limits,
                                                     theta_positions,
                                                     radial_frac,
                                                     nlayer);
 // Set error estimator
 Z2ErrorEstimator* error_estimator_pt=new Z2ErrorEstimator;
 mesh_pt()->spatial_error_estimator_pt()=error_estimator_pt;
 // Error targets for adaptive refinement
 mesh_pt()->max_permitted_error()=max_error_target;
 mesh_pt()->min_permitted_error()=min_error_target;
 // Set the boundary conditions for this problem: All nodal values are
 // free by default -- just pin the ones that have Dirichlet conditions
 // here.
 //Choose the conventional form by setting gamma to zero
 //The boundary conditions will be pseudo-traction free (d/dn = 0)
 ELEMENT::Gamma[0] = 0.0;
 ELEMENT::Gamma[1] = 0.0;
 ELEMENT::Gamma[2] = 0.0;

 //Loop over the boundaries
 unsigned num_bound = mesh_pt()->nboundary();
 for(unsigned ibound=0;ibound<num_bound;ibound++)
```

```
  {
   unsigned num_nod= mesh_pt()->nboundary_node(ibound);
   for (unsigned inod=0;inod<num_nod;inod++)
    {
     // Boundary 0 is the inlet symmetry boundary:
     // Boundary 1 is the tube wall
     // Pin all values
     if((ibound==0) || (ibound==1))
      {
       mesh_pt()->boundary_node_pt(ibound,inod)->pin(0);
       mesh_pt()->boundary_node_pt(ibound,inod)->pin(1);
       mesh_pt()->boundary_node_pt(ibound,inod)->pin(2);
      }
    }
  } // end loop over boundaries

 // Loop over the elements to set up element-specific
 // things that cannot be handled by constructor
 unsigned n_element = mesh_pt()->nelement();
 for(unsigned i=0;i<n_element;i++)
  {
   // Upcast from GeneralisedElement to the present element
   ELEMENT* el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(i));

   //Set the Reynolds number, etc
   el_pt->re_pt() = &Global_Physical_Variables::Re;
  }

 // Pin redudant pressure dofs
 RefineableNavierStokesEquations<3>::
  pin_redundant_nodal_pressures(mesh_pt()->element_pt());

 //Attach the boundary conditions to the mesh
 cout «"Number of equations: " « assign_eqn_numbers() « std::endl;

} // end_of_constructor


//=start_of_actions_before_newton_solve==================================
/// Set the inflow boundary conditions
//========================================================================
template<class ELEMENT>
void SteadyCurvedTubeProblem<ELEMENT>::actions_before_newton_solve()
{

 // (Re-)assign velocity profile at inflow values
 //--------------------------------------------
 unsigned ibound=0;
 unsigned num_nod= mesh_pt()->nboundary_node(ibound);
 for (unsigned inod=0;inod<num_nod;inod++)
  {
   // Recover coordinates of tube relative to centre position
   double x=mesh_pt()->boundary_node_pt(ibound,inod)->x(0) -
    1.0/Global_Physical_Variables::Delta;
   double z=mesh_pt()->boundary_node_pt(ibound,inod)->x(2);
   //Calculate the radius
   double r=sqrt(x*x+z*z);

   // Poiseuille-type profile for axial velocity (component 1 at the inlet)
   mesh_pt()->boundary_node_pt(ibound,inod)->
    set_value(1,(1.0-pow(r,2.0)));
  }

} // end_of_actions_before_newton_solve


//=start_of_doc_solution=================================================
/// Doc the solution
//========================================================================
template<class ELEMENT>
void SteadyCurvedTubeProblem<ELEMENT>::doc_solution()
{
 //Output file stream
 ofstream some_file;
 char filename[100];

 // Number of plot points
 unsigned npts;
 npts=5;

 //Need high precision for large radii of curvature
 //some_file.precision(10);
 // Output solution labelled by the Reynolds number
 snprintf(filename, sizeof(filename), "%s/soln_Re%g.dat",Doc_info.directory().c_str(),
         Global_Physical_Variables::Re);
 some_file.open(filename);
 mesh_pt()->output(some_file,npts);
```

```
 some_file.close();

} // end_of_doc_solution



//////////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////////
//////////////////////////////////////////////////////////////////////////


//=start_of_main=========================================================
/// Driver for 3D entry flow into a curved tube. If there are
/// any command line arguments, we regard this as a validation run
/// and perform only a single adaptation
//=======================================================================
int main(int argc, char* argv[])
{

 // Store command line arguments
 CommandLineArgs::setup(argc,argv);

 // Allow (up to) two rounds of fully automatic adapation in response to
 //-----------------------------------------------------------------------
 // error estimate
 //---------------
 unsigned max_adapt;
 double max_error_target,min_error_target;

 // Set max number of adaptations in black-box Newton solver and
 // error targets for adaptation
 if (CommandLineArgs::Argc==1)
  {
   // Up to two adaptations
   max_adapt=2;

   // Error targets for adaptive refinement
   max_error_target=0.001;
   min_error_target=0.00001;
  }
 // Validation run: Only one adaptation. Relax error targets
 // for faster solution
 else
  {
   // Validation run: Just one round of adaptation
   max_adapt=1;

   // Error targets for adaptive refinement
   max_error_target=0.02;
   min_error_target=0.002;
  }
 // end max_adapt setup

 // Set up doc info
 DocInfo doc_info;
 // Do Taylor-Hood elements
 //------------------------
 {
  // Set output directory
  doc_info.set_directory("RESLT_TH");

  // Step number
  doc_info.number()=0;

  // Build problem
  SteadyCurvedTubeProblem<RefineableQTaylorHoodElement<3> >
   problem(doc_info,min_error_target,max_error_target);

  cout « " Doing Taylor-Hood elements " « std::endl;

  // Solve the problem
  problem.newton_solve(max_adapt);
  // Doc solution after solving
  problem.doc_solution();
 }

 // Do Crouzeix-Raviart elements
 //------------------------
 {
  // Set output directory
  doc_info.set_directory("RESLT_CR");

  // Step number
  doc_info.number()=0;

  // Build problem
  SteadyCurvedTubeProblem<RefineableQCrouzeixRaviartElement<3> >
```

```
   problem(doc_info,min_error_target,max_error_target);

  cout « " Doing Crouzeix-Raviart elements " « std::endl;

  // Solve the problem
  problem.newton_solve(max_adapt);
  // Doc solution after solving
  problem.doc_solution();
 }

} // end_of_main
```

1.1 PDF file

A pdf version of this document is available. \