

Chapter 1

A real fluid-structure interaction problem: Finite Reynolds number flow in an oscillating elastic ring.

Our first "real" fluid-structure interaction problem: We study the finite-Reynolds number internal flow generated by the motion of an oscillating elastic ring and compare the results against asymptotic predictions.

```
//LIC// =====
//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.
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//LIC//=====
// Driver for 2D Navier Stokes flow interacting with an elastic ring

// Oomph-lib include files
#include "generic.h"
#include "navier_stokes.h"
#include "beam.h"

//Need to include templated meshes, so that all functions
//are instantiated for our particular element types.
#include "meshes/quarter_circle_sector_mesh.h"
#include "meshes/one_d_lagrangian_mesh.h"

using namespace std;

using namespace oomph;

//=====
/// Namespace for physical parameters
//=====
namespace Global_Physical_Variables
{

// Independent parameters:
//-----

/// Square of Womersly number (a frequency parameter)
```

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```
double Alpha_sq=50.0;

/// Density ratio of the solid and the fluid
double Density_ratio=1.0;

/// External Pressure
double Pext=0.0;

/// Poisson ratio
double Nu=0.49;

/// Nondimensional thickness of the beam
double H=0.05;

/// Perturbation pressure
double Pcos=0.0;

// Dependent parameters:
//-----
// Reynolds number
double Re;

// Reynolds x Strouhal number
double ReSt;

// Timescale ratio (non-dimensionation density)
double Lambda_sq;

// Stress ratio
double Q;

// Set the parameters that are used in the code as a function
// of the Womersley number, the density ratio and H
void set_params()
{
    cout << "\n\n====="
    cout << "\nSetting parameters. \n\n";
    cout << "Prescribed: Square of Womersley number: Alpha_sq = "
        << Alpha_sq << std::endl;
    cout << "Density ratio: Density_ratio = "
        << Density_ratio << std::endl;
    cout << "Wall thickness: H = "
        << H << std::endl;
    cout << "Poisson ratio: Nu = "
        << Nu << std::endl;
    cout << "Pressure perturbation: Pcos = "
        << Pcos << std::endl;

    Q=1.0/12.0*pow(H,3)/Alpha_sq;
    cout << "\nDependent: Stress ratio: Q = "
        << Q << std::endl;

    Lambda_sq=1.0/12.0*pow(H,3)*Density_ratio;
    cout << "Timescale ratio: Lambda_sq = "
        << Lambda_sq << std::endl;

    Re=Alpha_sq;
    cout << "Reynolds number: Re = "
        << Re << std::endl;

    ReSt=Re;
    cout << "Womersley number: ReSt = "
        << ReSt << std::endl;
    cout << "\n=====\n"
        << std::endl;
}

/// Non-FSI load function, a constant external pressure plus
/// a (small) sinusoidal perturbation of wavenumber two.
void pcos_load(const Vector<double>& xi, const Vector<double> &x,
               const Vector<double>& N, Vector<double>& load)
{
    for(unsigned i=0;i<2;i++)
        {load[i] = (Pext - Pcos*cos(2.0*xi[0]))*N[i];}
}

//=====
/// FSI Ring problem: a fluid-structure interaction problem in which
/// a viscous fluid bounded by an initially circular beam is set into motion
/// by a small sinusoidal perturbation of the beam (the domain boundary).
```

```

//=====================================================================
class FSIRingProblem : public Problem
{
    /// There are very few element types that will work for this problem.
    /// Rather than passing the element type as a template parameter to the
    /// problem, we choose instead to use a typedef to specify the
    /// particular element fluid used.
    typedef AlgebraicElement<RefineableQCrouzeixRaviartElement<2> > FLUID_ELEMENT;

    /// Typedef to specify the solid element used
    typedef FSIHermiteBeamElement SOLID_ELEMENT;

public:

    /// Constructor: Number of elements in wall mesh, amplitude of the
    /// initial wall deformation, amplitude of pcos perturbation and its duration.
    FSIRingProblem(const unsigned &n_element_wall,
                   const double& eps_ampl, const double& pcos_initial,
                   const double& pcos_duration);

    /// Update after solve (empty)
    void actions_after_newton_solve() {}

    /// Update before solve (empty)
    void actions_before_newton_solve() {}

    /// Update the problem specs before checking Newton
    /// convergence
    void actions_before_newton_convergence_check()
    {
        // Update the fluid mesh -- auxiliary update function for algebraic
        // nodes automatically updates no slip condition.
        Fluid_mesh_pt->node_update();
    }

    /// Update the problem specs after adaptation:
    void actions_after_adapt()
    {
        // The functions used to update the no slip boundary conditions
        // must be set on any new nodes that have been created during the
        // mesh adaptation process.
        // There is no mechanism by which auxiliary update functions
        // are copied to newly created nodes.
        // (because, unlike boundary conditions, they don't occur exclusively
        // at boundaries)

        // The no-slip boundary is boundary 1 of the mesh
        // Loop over the nodes on this boundary and reset the auxilliary
        // node update function
        unsigned n_node = Fluid_mesh_pt->nboundary_node(1);
        for (unsigned n=0;n<n_node;n++)
        {
            Fluid_mesh_pt->boundary_node_pt(1,n)->set_auxiliary_node_update_fct_pt(
                FSI_functions::apply_no_slip_on_moving_wall);
        }

        // (Re-)setup fsi: Work out which fluid dofs affect wall elements
        // the correspondance between wall dofs and fluid elements is handled
        // during the remeshing, but the "reverse" association must be done
        // separately.
        // We need to set up the interaction every time because the fluid element
        // adjacent to a given solid element's integration point may have changed
        // We pass the boundary between the fluid and solid meshes and pointers
        // to the meshes. The interaction boundary is boundary 1 of the 2D
        // fluid mesh.
        FSI_functions::setup_fluid_load_info_for_solid_elements<FLUID_ELEMENT,2>
            (this,1,Fluid_mesh_pt,Wall_mesh_pt);
    }

    /// Doc solution: Pass number of timestep, i (we append to tracefile
    /// after every timestep but do a full doc only at certain intervals),
    /// DocInfo object and tracefile
    void doc_solution(const unsigned& i, DocInfo& doc_info, ofstream& trace_file);

    /// Do dynamic run
    void dynamic_run();

private:

    /// Setup initial condition for both domains
    void set_initial_condition();

    /// Setup initial condition for wall
    void set_wall_initial_condition();

    /// Setup initial condition for fluid
    void set_fluid_initial_condition();
}

```

```

/// Element used for documenting displacement
SOLID_ELEMENT* Doc_displacement_elem_pt;

/// Pointer to wall mesh
OneDLagrangianMesh<SOLID_ELEMENT> *Wall_mesh_pt;

/// Pointer to fluid mesh
AlgebraicRefineableQuarterCircleSectorMesh<FLUID_ELEMENT> *Fluid_mesh_pt;

/// Pointer to geometric object that represents the undeformed wall shape
GeomObject* Undef_geom_pt;

/// Pointer to wall timestepper
Newmark<2>* Wall_time stepper_pt;

/// Pointer to fluid timestepper
BDF<2>* Fluid_time stepper_pt;

/// Pointer to node on coarsest mesh on which velocity is traced
Node* Veloc_trace_node_pt;

/// Amplitude of initial deformation
double Eps_ampl;

/// Initial pcos
double Pcos_initial;

/// Duration of initial pcos
double Pcos_duration;

};

//=====================================================================
/// Setup initial condition: When we're done here, all variables
/// represent the state at the initial time.
//=====================================================================
void FSIRingProblem::set_initial_condition()
{
    cout << "Setting wall ic" << std::endl;
    set_wall_initial_condition();

    cout << "Setting fluid ic" << std::endl;
    set_fluid_initial_condition();
}

//=====================================================================
/// Setup initial condition for fluid: Impulsive start
//=====================================================================
void FSIRingProblem::set_fluid_initial_condition()
{
    // Update fluid domain: Careful!!! This also applies the no slip conditions
    // on all nodes on the wall! Since the wall might have moved since
    // we created the mesh; we're therefore imposing a nonzero
    // velocity on these nodes. Must wipe this afterwards (done
    // by setting *all* velocities to zero) otherwise we get
    // an impulsive start from a very bizarre initial velocity
    // field! [Yes, it took me a while to figure this out...]
    Fluid_mesh_pt->node_update();

    // Assign initial values for the velocities;
    // pressures don't carry a time history and can be left alone.

    //Find number of nodes in fluid mesh
    unsigned n_node = Fluid_mesh_pt->nnode();

    // Loop over the nodes to set initial guess everywhere
    for(unsigned n=0;n<n_node;n++)
    {
        // Loop over velocity directions: Impulsive initial start from
        // zero velocity!
        for(unsigned i=0;i<2;i++)
        {
            Fluid_mesh_pt->node_pt(n)->set_value(i,0.0);
        }
    }

    // Do an impulsive start with the assigned velocity field
}

```

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Fluid_mesh_pt->assign_initial_values_impulsive();

}

//=====================================================================
/// Setup initial condition: Impulsive start either from
/// deformed or undeformed wall shape.
//=====================================================================
void FSIRingProblem::set_wall_initial_condition()
{
    // Geometric object that specifies the initial conditions:
    // A ring that is bucked in a 2-lobed mode
    GeomObject* ic_geom_object_pt=
        new PseudoBucklingRing(Eps_ampl,Global_Physical_Variables::H,2,2,
                               Wall_time stepper_pt);
    // Assign period of oscillation of the geometric object
    static_cast<PseudoBucklingRing*>(ic_geom_object_pt)->set_T(1.0);
    //Set initial time (to deform wall into max. amplitude)
    double time=0.25;
    // Assign initial radius of the object
    static_cast<PseudoBucklingRing*>(ic_geom_object_pt)->set_R_0(1.00);
    // Setup object that specifies the initial conditions:
    SolidInitialCondition* IC_pt = new SolidInitialCondition(ic_geom_object_pt);
    // Assign values of positional data of all elements on wall mesh
    // so that the wall deforms into the shape specified by IC object.
    SolidMesh::Solid_IC_problem.set_static_initial_condition(
        this,Wall_mesh_pt,IC_pt,time);
}

//=====================================================================
/// Document solution: Pass number of timestep, i; we append to trace file
/// at every timestep and do a full doc only after a certain number
/// of steps.
//=====================================================================
void FSIRingProblem::doc_solution(const unsigned& i,
                                   DocInfo& doc_info, ofstream& trace_file)
{
    // Full doc every nskip steps
    unsigned nskip=1; // ADJUST

    // If we at an integer multiple of nskip, full documentation.
    if (i%nskip==0)
    {
        doc_info.enable_doc();
        cout << "Full doc step " << doc_info.number()
            << " for time " << time stepper_pt()->time_pt()->time() << std::endl;
    }
    //Otherwise, just output the trace file
    else
    {
        doc_info.disable_doc();
        cout << "Only trace for time "
            << time stepper_pt()->time_pt()->time() << std::endl;
    }

    // If we are at a full documentation step, output the fluid solution
    if (doc_info.is_doc_enabled())
    {
        //Variables used in the output file.
        ofstream some_file; char filename[100];
        //Construct the output filename from the doc_info number and the
        //output directory
        sprintf(filename, sizeof(filename), "%s/soln%u.dat", doc_info.directory().c_str(),
               doc_info.number());
        //Open the output file
        some_file.open(filename);
        /// Output the solution using 5x5 plot points
        Fluid_mesh_pt->output(some_file,5);
        //Close the output file
        some_file.close();
    }
    //Temporary vector to give the local coordinate at which to document
    //the wall displacement
    Vector<double> s(1,1.0);
    // Write to the trace file:
    trace_file << time_pt()->time()
        //Document the displacement at the end of the the chosen element
        << " " << Doc_displacement_elem_pt->interpolated_x(s,1)
        << " " << Veloc_trace_node_pt->x(0)
        << " " << Veloc_trace_node_pt->x(1)
        << " " << Veloc_trace_node_pt->value(0)
        << " " << Veloc_trace_node_pt->value(1)
}

```

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    << " " << Fluid_mesh_pt->n_element()
    << " " << ndof()
    << " " << Fluid_mesh_pt->n_refinement_overruled()
    << " " << Fluid_mesh_pt->max_error()
    << " " << Fluid_mesh_pt->min_error()
    << " " << Fluid_mesh_pt->max_permitted_error()
    << " " << Fluid_mesh_pt->min_permitted_error()
    << " " << Fluid_mesh_pt->max_keep_unrefined();

// Output the number of the corresponding full documentation
// file number (or -1 if no full doc was made)
if (doc_info.is_doc_enabled())
{trace_file << " " << doc_info.number() << " ";
else {trace_file << " " << -1 << " ";}
}

//End the trace file
trace_file << std::endl;

// Increment counter for full doc
if (doc_info.is_doc_enabled()) {doc_info.number()++;}
}

//=====================================================================
/// Constructor for FSI ring problem. Pass number of wall elements
/// and length of wall (in Lagrangian coordinates) amplitude of
/// initial deformation, pcos perturbation and duration.
//=====================================================================
FSIRingProblem::FSIRingProblem(const unsigned& N,
                               const double& eps_ampl, const double& pcos_initial,
                               const double& pcos_duration) :
Eps_ampl(eps_ampl), Pcos_initial(pcos_initial),
Pcos_duration(pcos_duration)
{
//-----
// Create timesteppers
//-----
// Allocate the wall timestepper and add it to the problem's vector
// of timesteppers
Wall_time stepper_pt = new Newmark<2>;
add_time stepper_pt(Wall_time stepper_pt);

// Allocate the fluid timestepper and add it to the problem's Vector
// of timesteppers
Fluid_time stepper_pt = new BDF<2>;
add_time stepper_pt(Fluid_time stepper_pt);

//-----
// Create the wall mesh
//-----

// Undefomed wall is an elliptical ring
Undef_geom_pt = new Ellipse(1.0,1.0);

//Length of wall in Lagrangian coordinates
double L = 2.0*atan(1.0);

//Now create the (Lagrangian!) mesh
Wall_mesh_pt = new
OneDLagrangianMesh<SOLID_ELEMENT>(N,L,Undef_geom_pt,Wall_time stepper_pt);

//-----
// Set the boundary conditions for wall mesh (problem)
//-----
// Bottom boundary: (Boundary 0)
// No vertical displacement
Wall_mesh_pt->boundary_node_pt(0,0)->pin_position(1);
// Zero slope: Pin type 1 dof for displacement direction 0
Wall_mesh_pt->boundary_node_pt(0,0)->pin_position(1,0);
// Top boundary: (Boundary 1)
// No horizontal displacement
Wall_mesh_pt->boundary_node_pt(1,0)->pin_position(0);
// Zero slope: Pin type 1 dof for displacement direction 1
Wall_mesh_pt->boundary_node_pt(1,0)->pin_position(1,1);

//-----
// Create the fluid mesh:
//-----

// Fluid mesh is suspended from wall between the following Lagrangian
// coordinates:
double xi_lo=0.0;
double xi_hi=L;

// Fractional position of dividing line for two outer blocks in mesh
double fract_mid=0.5;
//Create a geometric object that represents the wall geometry from the

```

```

//wall mesh (one Lagrangian, two Eulerian coordinates).
MeshAsGeomObject *wall_mesh_as_geometric_object_pt
= new MeshAsGeomObject(Wall_mesh_pt);

// Build fluid mesh using the wall mesh as a geometric object
Fluid_mesh_pt = new AlgebraicRefineableQuarterCircleSectorMesh<FLUID_ELEMENT>
(wall_mesh_as_geometric_object_pt,
 xi_lo, fract_mid, xi_hi, Fluid_time_stepper_pt);

// Set the error estimator
Z2ErrorEstimator* error_estimator_pt=new Z2ErrorEstimator;
Fluid_mesh_pt->spatial_error_estimator_pt()=error_estimator_pt;

// Extract pointer to node at center of mesh
unsigned nnode=Fluid_mesh_pt->finite_element_pt(0)->nnode();
Veloc_trace_node_pt=Fluid_mesh_pt->finite_element_pt(0)->node_pt(nnode-1);
//-----
// Set the fluid boundary conditions
//-----

// Bottom boundary (boundary 0):
{
unsigned n_node = Fluid_mesh_pt->nboundary_node(0);
for (unsigned n=0;n<n_node;n++)
{
    // Pin vertical velocity
    Fluid_mesh_pt->boundary_node_pt(0,n)->pin(1);
}
}

// Ring boundary (boundary 1):
// No slip; this also implies that the velocity needs
// to be updated in response to wall motion
{
unsigned n_node = Fluid_mesh_pt->nboundary_node(1);
for (unsigned n=0;n<n_node;n++)
{
    // Which node are we dealing with?
    Node* node_pt=Fluid_mesh_pt->boundary_node_pt(1,n);

    // Set auxiliary update function pointer
    node_pt->set_auxiliary_node_update_fct_pt(
        FSI_functions::apply_no_slip_on_moving_wall);

    // Pin both velocities
    for(unsigned i=0;i<2;i++) {node_pt->pin(i);}
}
}

// Left boundary (boundary 2):
{
unsigned n_node = Fluid_mesh_pt->nboundary_node(2);
for (unsigned n=0;n<n_node;n++)
{
    // Pin horizontal velocity
    Fluid_mesh_pt->boundary_node_pt(2,n)->pin(0);
}
}

//-----
// Add the submeshes and build global mesh
// -----
// Wall mesh
add_sub_mesh(Wall_mesh_pt);

//Fluid mesh
add_sub_mesh(Fluid_mesh_pt);

// Combine all submeshes into a single Mesh
build_global_mesh();

//-----
// Finish problem setup
// -----

//Find number of elements in fluid mesh
unsigned n_element = Fluid_mesh_pt->nelement();

// Loop over the fluid elements to set up element-specific
// things that cannot be handled by constructor
for(unsigned e=0;e<n_element;e++)
{
    // Upcast from FiniteElement to the present element
    FLUID_ELEMENT *el_pt

```

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= dynamic_cast<FLUID_ELEMENT*>(Fluid_mesh_pt->element_pt(e));

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

el_pt->evaluate_shape_derivs_by_direct_fd();

// el_pt->evaluate_shape_derivs_by_chain_rule();
// el_pt->enable_always_evaluate_dresidual_dnodal_coordinates_by_fd();

// if (e==0)
// {
//     el_pt->disable_always_evaluate_dresidual_dnodal_coordinates_by_fd();
// }
// else
// {
//     el_pt->enable_always_evaluate_dresidual_dnodal_coordinates_by_fd();
// }

//el_pt->evaluate_shape_derivs_by_direct_fd();

}

//Loop over the solid elements to set physical parameters etc.
unsigned n_wall_element = Wall_mesh_pt->n_element();
for(unsigned e=0;e<n_wall_element;e++)
{
    //Cast to proper element type
    SOLID_ELEMENT *el_pt = dynamic_cast<SOLID_ELEMENT*>(
        Wall_mesh_pt->element_pt(e));

    //Set physical parameters for each element:
    el_pt->h_pt() = &Global_Physical_Variables::H;
    el_pt->lambd_sq_pt() = &Global_Physical_Variables::Lambda_sq;

    //Function that specifies the external load Vector
    el_pt->load_vector_fct_pt() = &Global_Physical_Variables::pcos_load;

    // Function that specifies the load ratios
    el_pt->q_pt() = &Global_Physical_Variables::Q;

    //Assign the undeformed beam shape
    el_pt->undeformed_beam_pt() = Undef_geom_pt;
}
// Establish control displacement: (even if no displacement control is applied
// we still want to doc the displacement at the same point)

// Choose element: (This is the last one)
Doc_displacement_elem_pt = dynamic_cast<SOLID_ELEMENT*>(
    Wall_mesh_pt->element_pt(n_wall_element-1));

// Setup fsi: Work out which fluid dofs affect the wall elements
// the correspondance between wall dofs and fluid elements is handled
// during the remeshing, but the "reverse" association must be done
// separately.
// We pass the boundary between the fluid and solid meshes and pointers
// to the meshes. The interaction boundary is boundary 1 of the
// 2D fluid mesh.
FSI_functions::setup_fluid_load_info_for_solid_elements<FLUID_ELEMENT,2>
(this,1,Fluid_mesh_pt,Wall_mesh_pt);

// Do equation numbering
cout << "# of dofs " << assign_eqn_numbers() << std::endl;
}

//=====================================================================
/// Solver loop to perform unsteady run
//=====================================================================
void FSIRingProblem::dynamic_run()
{
    // Setup documentation
    //-----

    /// Label for output
    DocInfo doc_info;

    // Output directory
    doc_info.set_directory("RESLT");

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

    //Open a trace file
    ofstream trace_file("RESLT/trace_ring.dat");
    // Write header for trace file

```

```

trace_file << "VARIABLES=\"time\", \"V_c_t_r_l\"";
trace_file << ", \"x<sub>1</sub><sup>(track)</sup>\"";
trace_file << ", \"x<sub>2</sub><sup>(track)</sup>\"";
trace_file << ", \"u<sub>1</sub><sup>(track)</sup>\"";
trace_file << ", \"u<sub>2</sub><sup>(track)</sup>\"";
trace_file << ", \"N<sub>element</sub>\"";
trace_file << ", \"N<sub>dof</sub>\"";
trace_file << "# of under-refined elements";
trace_file << "max. error";
trace_file << "min. error";
trace_file << "max. permitted error";
trace_file << "min. permitted error";
trace_file << "max. permitted # of unrefined elements";
trace_file << "doc number";
trace_file << std::endl;

// Initialise timestepping
// -----
// Number of steps
unsigned nstep=300;

// Nontrivial command line input: validation: only do three steps
if (CommandLineArgs::Argc>1)
{
    nstep=1;
    cout << "Only doing nstep steps for validation: " << nstep << std::endl;
}

// Set initial timestep
double dt=0.004;

// Set initial value for dt -- also assigns weights to the timesteppers
initialise_dt(dt);

// Set physical parameters
// -----
using namespace Global_Physical_Variables;

// Set Womersley number
Alpha_sq=100.0; // 50.0; // ADJUST

// Set density ratio
Density_ratio=10.0; // 0.0; ADJUST

// Wall thickness
H=1.0/20.0;

// Set external pressure
Pext=0.0;

// Perturbation pressure
Pcos=Pcos_initial;

// Assign/doc corresponding computational parameters
set_params();

// Refine uniformly and assign initial conditions
// -----
// Refine the problem uniformly
refine_uniformly();
refine_uniformly();

// This sets up the solution at the initial time
set_initial_condition();

// Set targets for spatial adaptivity
// -----
// Max. and min. error for adaptive refinement/unrefinement
Fluid_mesh_pt->max_permitted_error()=1.0e-2;
Fluid_mesh_pt->min_permitted_error()=1.0e-3;

// Don't allow refinement to drop under given level
Fluid_mesh_pt->min_refinement_level()=2;

// Don't allow refinement beyond given level
Fluid_mesh_pt->max_refinement_level()=6;

// Don't bother adapting the mesh if no refinement is required
// and if less than ... elements are to be merged.
Fluid_mesh_pt->max_keep_unrefined()=20;

// Doc refinement targets

```

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```
Fluid_mesh_pt->doc_adaptivity_targets(cout);

// Do the timestepping
//-----
// Reset initial conditions after refinement for first step only
bool first=true;

//Output initial data
doc_solution(0,doc_info,trace_file);

// {
//   unsigned nel=Fluid_mesh_pt->n(element());
//   for (unsigned e=0;e<nel;e++)
//   {
//     std::cout << "\n\nEl: " << e << std::endl << std::endl;
//     FiniteElement* el_pt=Fluid_mesh_pt->finite_element_pt(e);
//     unsigned n_dof=el_pt->ndof();
//     Vector<double> residuals(n_dof);
//     DenseDoubleMatrix jacobian(n_dof,n_dof);
//     el_pt->get_jacobian(residuals,jacobian);
//   }
//   exit(0);
// }

// Time integration loop
for(unsigned i=1;i<=nstep;i++)
{
  // Switch doc off during solve
  doc_info.disable_doc();

  // Solve
  unsigned max_adapt=1;
  unsteady_newton_solve(dt,max_adapt,first);

  // Now we've done the first step
  first=false;

  // Doc solution
  doc_solution(i,doc_info,trace_file);

  // Switch off perturbation pressure
  if (time_pt()->time()>Pcos_duration) {Pcos=0.0;}
}

}

//=====================================================================
// Driver for fsi ring test problem
//=====================================================================
int main(int argc, char* argv[])
{

  // Store command line arguments
  CommandLineArgs::setup(argc,argv);
  // Number of elements
  unsigned nelem = 13;

  // Perturbation pressure
  double pcos_initial=1.0e-6; // ADJUST

  // Duration of initial pcos perturbation
  double pcos_duration=0.3; // ADJUST

  // Amplitude of initial deformation
  double eps_ampl=0.0; // ADJUST

  //Set up the problem
  FSIRingProblem problem(nelem,eps_ampl,pcos_initial,pcos_duration);

  // Do parameter study
  problem.dynamic_run();
}
```

1.1 PDF file

A [pdf version](#) of this document is available. \