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► **To cite this version:**

Yongxing Wang, Olivier Pironneau. A class of fluid-structure interaction problems with analytical solutions. International Journal for Numerical Methods in Engineering, In press. hal-04580186v1

HAL Id: hal-04580186

<https://hal.science/hal-04580186v1>

Submitted on 24 May 2024 (v1), last revised 27 May 2024 (v2)

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A class of fluid-structure interaction problems with analytical solutions

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Abstract

Analytical solutions to Fluid-Structure Interaction (FSI) problems are almost absent in the literature. However, they are not only essential for understanding the intricate coupling dynamics between fluids and solids, but they also serve as benchmarks for validating and analysing the convergence of numerical algorithms. In this paper, we derive two analytical and one semi-analytical solutions for three FSI problems, spanning a class of solutions by varying their geometrical and physical parameters. All solutions exhibit complex nonlinear behaviours, which we validate through numerical simulations using a monolithic method. These three FSI problems are described in the cylindrical coordinates, drawing inspiration from Couette flow, with two of them featuring a moving fluid-solid interface and the third incorporating a nonlinear constitutive solid model. To the best of our knowledge, for the first time, we present FSI problems with analytical solutions that include a moving interface.

Keywords: Fluid-structure interaction, Analytical solution, Finite element, Monolithic method, One-velocity field

1. Introduction

Fluid-Structure Interaction (FSI) problems are prevalent across various fields, including spacecraft parachute dynamics [1], biomedical science [1–4], wind-turbine aerodynamics [5–7], and fixed or floating structures interacting with ocean waves [8–11], and so on. For most FSI problems, analytical solutions of the controlling equations are impossible to obtain, whereas laboratory experiments are complex, expensive and limited in scope. Therefore, numerical simulations play an important role in order to understand the fundamental physics involved in the complex interaction between fluids and structures.

1.1. A brief summary of numerical methods for fluid-structure interactions

Numerical methods for FSI problems have rapidly advanced over recent decades. Classical partitioned or segregated methods, as referenced in [1, 12–31], utilise a single interface-fitted mesh to solve for both fluid velocity and solid displacement. These methods represent

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some of the earliest numerical approaches developed for FSI problems and are still evolving, particularly in terms of parallelisation [25, 29], efficiency [26, 28], stability, accuracy [30], and adaptivity [27, 30, 31]. For two-way coupling (or strong coupling) FSI problems, partitioned methods iteratively solve for the fluid and solid problems separately. They exchange information across the fluid-solid interface until achieving a balance of variables at the interface. The advantage of classical partitioned methods is their relative ease of implementation, often based on the coupling of existing fluid and solid code. However, their drawback lies in the difficulty of guaranteeing convergence during iteration, especially when there is rapid energy exchange between the fluid and solid at the interface [19, 20]. A simplified version of these two-way partitioned methods is the one-way FSI method. In this method, only the fluid problem is solved explicitly, while the solid deforms passively by following the fluid fields. It provides an updated boundary condition for the fluid problem for every time frame [32–34].

Monolithic methods were developed to overcome the limitations of partitioned methods, which solve the fluid and solid equations within a single equation system. This approach has gained widespread acceptance as a more robust numerical method compared to classic partitioned methods. Initially, monolithic methods were based on an ALE interface-fitted mesh. They solve for fluid velocity, pressure, solid displacement, and use a Lagrange multiplier to enforce continuity at the fluid-solid interface [4, 35–37].

Recent advancements in monolithic methods have introduced the use of a background Cartesian grid with locally cut triangles to accommodate the fluid-solid interface, named as the locally modified FEM [38–41]. This method solves for the variables of fluid velocity and pressure, as well as solid displacement or velocity. In comparison to traditional ALE methods, it circumvents the need for a moving mesh and is proficient in handling arbitrarily large solid deformations. However, a difficulty lies in the management of local anisotropic FEM mesh—Edge stabilisation techniques [42] are introduced to enhance the stability.

Monolithic methods have also evolved to use two meshes [43–45]. This approach addresses fluid velocity, pressure, and solid displacement while using a distributed Lagrange multiplier to ensure velocity consistency between the meshes. Another variation is the cutFEM-based FSI method [46, 47], which extends the solid foreground mesh to envelop a surrounding artificial fluid mesh with a fitted interface. This method involves cutting through local elements around the interface for numerical quadrature without modifying local degrees of freedom, unlike the locally modified method. However, stability issues arise due to possible irregularities in local meshes, leading to the adoption of Nitsche-type interface coupling strategies with ghost penalty terms [48] to guarantee stability. The initial version of this cutFEM-based approach was presented in [49] as a partitioned approach.

Alternatively, monolithic methods have been adapted to employ a single mesh without interface fitting, known as the fully Eulerian formulation [50–56]. These methods use an Initial Points (IP) set to capture the fluid-structure interface, extending the unknown variables across the entire domain with a characteristic function. The FSI system is solved in a monolithic manner.

Recently, we developed a one-velocity method that solves for a single velocity field across the entire FSI domain, using either a single interface-fitted mesh [57–60] or two meshes [61–64]. In this one-velocity method, the solid equations are first expressed in terms of velocity,

automatically ensuring velocity consistency at the fluid-solid interface with one interface-fitted mesh. When using two meshes, finite element isoparametric interpolation is employed to maintain velocity consistency. We shall benchmark this one-velocity monolithic method against the three (semi-)analytical FSI problems proposed in this paper, concurrently, the analytical solutions will also be validated through this numerical method.

1.2. Analytical solutions in special computational domains

Analytical solutions to the Navier-Stokes equation may only be obtained for simple geometries with additional assumptions, utilising symmetry to reduce the equation to lower dimensions, such as the Couette flow between two concentric cylinders [65, 66], or the pulsatile flow in a pipe [67]. Both the Couette flow and the pulsatile flow can be modelled in a cylindrical coordinate system: $r - \theta - z$ are radial, circumferential, and axial coordinates respectively as shown in Figure 1; exploring the symmetry, the former may be reduced to a problem on $r - \theta$ plane while the latter on $r - z$ plane. Additional assumptions of the velocity profiles of the Couette and the pulsatile flow can further reduce them to one-dimensional problems, which may be solved analytically.

Analytical solutions of FSI problems, where Navier-Stokes equations are coupled with solid equations, have rarely been studied. Building on the Couette and pulsatile fluid flow, analytical FSI problems may be created to fill this gap in the FSI community. In a recent study [68], analytical solutions of the pulsatile flow in an elastic pipe have been derived, which is reduced to a one-dimensional ODE based on the assumption that the fluid velocity and solid displacement are axisymmetric and axially invariant – reduced to a 2D problem on $r - z$ plane, which only have the axial components. In this paper, we consider the Couette flow around an elastic solid as shown in Figure 1, and also assume that the fluid velocity and solid displacement are axisymmetric and axially invariant – reduced to a 2D problem on $r - \theta$ plane. However, depending on the boundary conditions, the velocity and displacement fields have either the radial or circumferential component: Problem II and III respectively in Figure 2 (b). Similar to Couette flow between two parallel plates, we will also consider an FSI problem between two parallel plates (Problem I) as shown in Figure 2 (a). Notice that it is also possible to consider an analytical FSI problem by applying a shearing boundary condition as shown in Figure 2 (a), in which case both the velocity and displacement fields only have components in the vertical direction. However, a very similar scenario has been studied in [68] albeit using the pulsatile-flow boundary conditions applied at the inlet and outlet. Therefore, we shall not consider this case in the current paper and readers may refer to [68] for the corresponding analysis.

The rest of this paper is organised as follows: the partial differential equations of the FSI problems are introduced in Section 2, followed by a discussion of the three FSI problems in Sections 3, 4, and 5 respectively. In each of these sections, the FSI problem is described first, followed by a detailed analysis and derivation of its analytical solution, with numerical validation provided finally. Conclusions are drawn in Section 6.

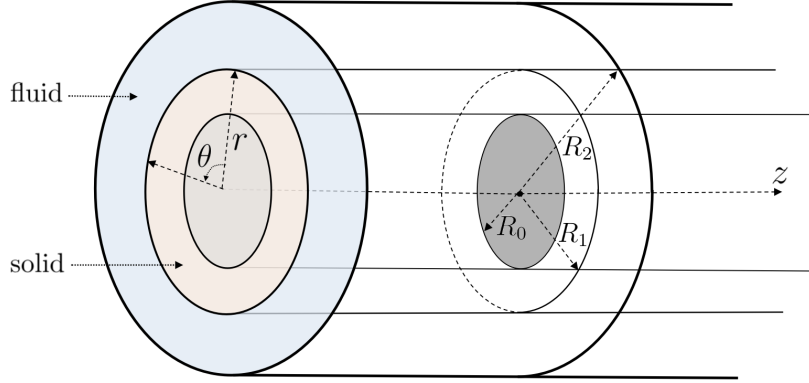


Figure 1: FSI diagram of an elastic solid and viscous fluid between concentric cylinders (R_0 and R_2) with a fixed-rod being the middle cylinder.

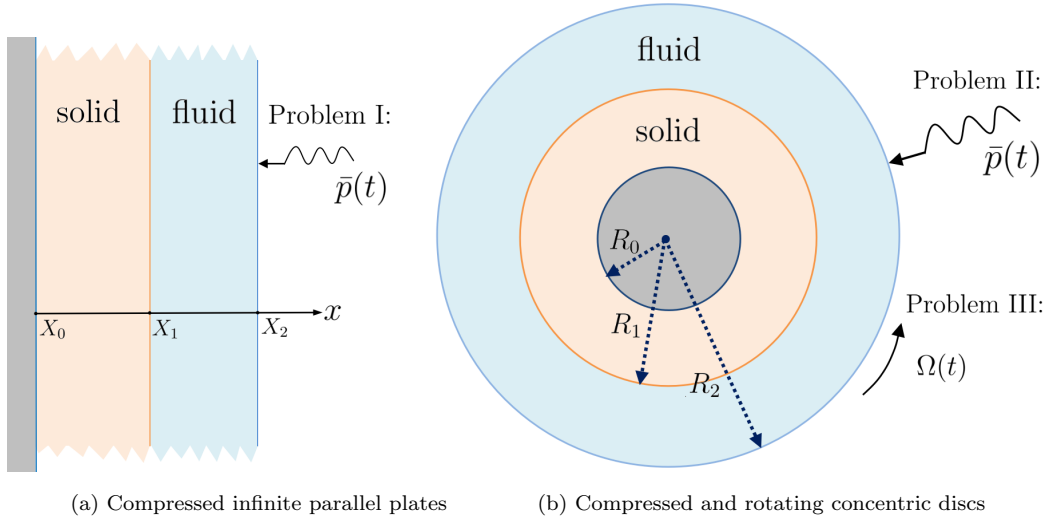


Figure 2: In problem I and II, a periodic normal stress is enforced at outer fluid boundaries, compressing the solids due to the compression of the fluids. In problem III, a periodic circumferential velocity is prescribed at the outer fluid boundary, causing the solid disc to rotate forward and backward due to the rotating fluid.

95 2. FSI equations

In this section, we introduce the partial differential equations for the three fluid-structure interaction problems as illustrated in Figure 2. For the first two cases, a periodic normal force is prescribed at the outer boundary of the fluid, as depicted, causing the solid to be propelled by the fluid and move along the normal/radial direction. For the third case, a periodic velocity is prescribed at the outer boundary of the fluid along the circumferential direction, leading to the solid being dragged to rotate forward and backward.

An incompressible Newtonian fluid is utilised for all the three problems in this paper, described as:

$$\rho^f \dot{\mathbf{u}} = \mu^f \nabla \cdot \nabla \mathbf{u} - \nabla p^f, \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (2)$$

105 Where \mathbf{u} represents the velocity vector and p^f denotes the pressure, with ρ^f and μ^f representing the fluid density and viscosity parameters respectively. $\dot{\mathbf{u}} = \frac{d}{dt}\mathbf{u} = \partial_t\mathbf{u} + \mathbf{u} \cdot \nabla\mathbf{u}$ is the total derivative of time.

Two solid models are considered in this paper. In problem I and II, we employ a compressible linear elastic solid described in the reference configuration:

$$\rho^s \ddot{\mathbf{d}} = \mu^s \hat{\nabla} \cdot \left(\hat{\nabla}^\top \mathbf{d} + \hat{\nabla} \mathbf{d} \right) + \lambda^s \hat{\nabla} (\hat{\nabla} \cdot \mathbf{d}), \quad (3)$$

110 where μ^s and λ^s are the Lamé constants, ρ^s is the solid density, and \mathbf{d} is the displacement vector. In problem III, we use an incompressible hyperelastic neo-Hookean model described in the current configuration:

$$\rho^s \ddot{\mathbf{d}} = \mu^s \nabla \cdot (\mathbf{F}\mathbf{F}^\top - \mathbf{I}) - \nabla p^s. \quad (4)$$

In the above equations (3) and (4), $\ddot{\mathbf{d}} = \frac{d^2}{dt^2}\mathbf{d}$ represents the second-order material derivative with respect to time. The FSI system can be closed by appropriate boundary and initial conditions. As shown in the Figure 2, we shall use a wall-boundary at X_0 or R_0 for all the three problems. At the outer fluid boundary, either a normal stress (Problem I and II) or a tangential velocity profile is prescribed. At the fluid-solid interface (X_1 or R_1), the continuity of the velocity and the continuity of the normal stress are applied. We shall discuss details of these boundary conditions, as well as the initial conditions, separately for the three specific problems in the following sections.

In the above, ∇ and $\hat{\nabla}$ represent the Nabla operator in the current and reference configurations respectively. Equations (1) to (3) do not specify a coordinate system. In the Cartesian coordinate system, we use $X\mathbf{i} + Y\mathbf{j}$ to denote a vector in the reference configuration, and $x\mathbf{i} + y\mathbf{j}$ to denote a vector in the current configuration, with $\mathbf{i} = (1, 0)^\top$ and $\mathbf{j} = (0, 1)^\top$ being the basis vectors. In the polar coordinate system, we use $r\mathbf{e}_r$ and $R\hat{\mathbf{e}}_r$ to represent vectors in the current and reference configurations respectively. The polar basis vectors $\mathbf{e}_r - \mathbf{e}_\theta$ (or $\hat{\mathbf{e}}_r - \hat{\mathbf{e}}_\theta$) are functions of θ (or $\hat{\theta}$) and can be derived as follows: since $(x, y) = (r \cos \theta, r \sin \theta)$,

$$\mathbf{e}_r = \frac{\partial_r(x, y)}{|\partial_r(x, y)|} = (\cos \theta, \sin \theta)^\top, \quad \mathbf{e}_\theta = \frac{\partial_\theta(x, y)}{|\partial_\theta(x, y)|} = (-\sin \theta, \cos \theta)^\top. \quad (5)$$

125 Similarly, $\hat{\mathbf{e}}_r = (\cos \hat{\theta}, \sin \hat{\theta})^\top$ and $\hat{\mathbf{e}}_\theta = (-\sin \hat{\theta}, \cos \hat{\theta})^\top$. The relation between $(\mathbf{e}_r, \mathbf{e}_\theta)$ and $(\hat{\mathbf{e}}_r, \hat{\mathbf{e}}_\theta)$ is

$$\hat{\mathbf{e}}_r = \cos \alpha \mathbf{e}_r - \sin \alpha \mathbf{e}_\theta, \quad \hat{\mathbf{e}}_\theta = \sin \alpha \mathbf{e}_r + \cos \alpha \mathbf{e}_\theta, \quad (6)$$

where $\alpha = \theta - \hat{\theta}$ is the angular displacement.

It can also be observed that the relationship of the bases between these two coordinate systems is given by:

$$(\mathbf{e}_r, \mathbf{e}_\theta) \mathbf{Q} = (\mathbf{i}, \mathbf{j}) \quad (7)$$

where

$$\mathbf{Q} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \quad (8)$$

With the above notations, it is straightforward to compute the Jacobi matrix

$$\mathbf{J} = \partial_{(r,\theta)}(x, y) = \begin{pmatrix} \cos \theta & \sin \theta \\ -r \sin \theta & r \cos \theta \end{pmatrix} \quad (9)$$

and its inverse

$$\mathbf{J}^{-1} = \partial_{(x,y)}(r, \theta) = \frac{1}{r} \begin{pmatrix} r \cos \theta & -\sin \theta \\ r \sin \theta & \cos \theta \end{pmatrix} \quad (10)$$

and further the Nabla operator in the polar coordinate system:

$$\nabla = (\mathbf{i}, \mathbf{j})\partial_{(x,y)} = (\mathbf{e}_r, \mathbf{e}_\theta) \mathbf{Q} \mathbf{J}^{-1} \partial_{(r,\theta)} = (\mathbf{e}_r, \mathbf{e}_\theta/r) \partial_{(r,\theta)} = \mathbf{e}_r \partial_r + \mathbf{e}_\theta \frac{1}{r} \partial_\theta. \quad (11)$$

The Nabla operator is a first-order tensor. The derivative of the polar basis:

$$\begin{pmatrix} \partial_r \mathbf{e}_r & \partial_r \mathbf{e}_\theta \\ \partial_\theta \mathbf{e}_r & \partial_\theta \mathbf{e}_\theta \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ \mathbf{e}_\theta & -\mathbf{e}_r \end{pmatrix} = \mathbf{e}_\theta (\mathbf{e}_r \mathbf{e}_\theta) - \mathbf{e}_r (\mathbf{e}_\theta \mathbf{e}_\theta) \quad (12)$$

will also be used to derive the control equations in the following sections, which is a second-order tensor, with basis $\mathbf{e}_r \mathbf{e}_\theta$ being $\mathbf{e}_r \otimes \mathbf{e}_\theta$ for short, etc. We can further compute the dot product of two Nabla operators which is a scalar:

$$\nabla \cdot \nabla = \left(\mathbf{e}_r \partial_r + \mathbf{e}_\theta \frac{1}{r} \partial_\theta \right) \cdot \left(\mathbf{e}_r \partial_r + \mathbf{e}_\theta \frac{1}{r} \partial_\theta \right) = \partial_{rr} + \frac{1}{r} \partial_r + \frac{1}{r^2} \partial_{\theta\theta}. \quad (13)$$

Notice that the operators in (11), (12), and (13) take the same form in the reference coordinate system.

Remark 1. *A special feature of applying normal stress (Problem I and II) is the creation of a moving interface, rendering the FSI problem non-trivial and challenging. In contrast, for Problem III and the pulsatile-type FSI problems described in [68], the FSI interface remains stationary. Here, the complexity lies more in the non-linear solid constitutive model.*

Remark 2. *For Problem I and II, although we consider a linear constitutive model for the solid, the linearity is in the reference configuration – highly non-linear if expressed in the current configuration, while the fluid equation is expressed in the current configuration. This inconsistency makes the FSI problems more challenging and interesting.*

3. Problem I: compressed parallel plates

For the computational geometry and normal-force boundary condition shown in Figure 2 (a), we assume that only the horizontal velocity component u is non-zero, which, together with the pressure p , depends only on x and t . The fluid equations (1) and (2) reduce to one-dimensional PDEs as follows:

$$\rho_f \dot{u}(x, t) = -p'(x, t), \quad (14)$$

$$u'(x, t) = 0, \quad (15)$$

Similarly, we assume the solid displacement only has the horizontal component d , which is a function of X and t . Then the solid equation (3) is reduced to

$$\rho^s \ddot{d}(X, t) = (2\mu^s + \lambda^s) d''(X, t). \quad (16)$$

The fluid equation (14) is expressed in the current or physical domain corresponding to the reference domain $[X_1, X_2]$, while the solid (16) equation is expressed directly in the reference domain $[X_0, X_1]$. We use the Lagrangian mapping to find the current domain for the fluid, i.e., extending the solid displacement $d(X, t)$ ($X \in [X_0, X_1]$) to the displacement of the fluid particles $\xi(X, t)$ ($X \in [X_1, X_2]$), with $\xi(X_1, t) = d(X_1, t)$ at the interface. Let $x_1(t) = X_1 + \xi(X_1, t)$ and $x_2(t) = X_2 + \xi(X_2, t)$, then $x(X, t) = X + \xi(X, t)$ with $X \in [X_1, X_2]$ represents a general point in the current domain $[x_1(t), x_2(t)]$.

The FSI system is completed with the following boundary conditions:

$$d(X_0, t) = 0, \quad (17)$$

$$\dot{d}(X_1, t) = u(x_1(t), t), \quad (18)$$

$$(2\mu^s + \lambda^s) d'(X_1, t) = -p(x_1(t), t), \quad (19)$$

$$p(x_2(t), t) = \bar{p}(t). \quad (20)$$

3.1. Analytical solution

With $\omega = \phi \sqrt{(2\mu^s + \lambda^s)/\rho^s}$,

$$d(X, t) = \frac{a}{\omega} \sin(\phi(X - X_0)) \sin(\omega t), \quad (21)$$

is the general solution of (16), and also satisfies the homogeneous boundary condition (17) and initial condition $d(X, 0) = 0$.

$$\dot{d}(X_1, t) = a \sin(\phi(X_1 - X_0)) \cos(\omega t) \quad (22)$$

is the velocity at the interface and also equivalent to the fluid velocity, $u(x, t)$, across the fluid domain $[X_1, X_2]$, since (15): $u'(x, t) = 0 \Rightarrow u(x, t)$ is constant in x . Therefore, according to (14), the pressure is

$$p'(x, t) = \omega \rho^f a \sin(\phi(X_1 - X_0)) \sin(\omega t), \quad (23)$$

or

$$p(x, t) = p^0(t) + x \omega \rho^f a \sin(\phi(X_1 - X_0)) \sin(\omega t). \quad (24)$$

Matching the normal stresses at the interface (19) gives

$$\begin{aligned} p^0(t) + (X_1 + d(X_1, t)) \omega \rho^f a \sin(\phi(X_1 - X_0)) \sin(\omega t) \\ = - \frac{a \phi (2\mu^s + \lambda^s)}{\omega} \cos(\phi(X_1 - X_0)) \sin(\omega t), \end{aligned} \quad (25)$$

and this equations determines $p^0(t)$:

$$\begin{aligned} p^0(t) = - (X_1 + d(X_1, t)) \omega \rho^f a \sin(\phi(X_1 - X_0)) \sin(\omega t) \\ - \frac{a \phi (2\mu^s + \lambda^s)}{\omega} \cos(\phi(X_1 - X_0)) \sin(\omega t). \end{aligned} \quad (26)$$

Let the initial displacement and velocity be $d(X, 0) = 0$ and $u(x, 0) = a \sin(\phi(X_1 - X_0))$ respectively. Since the fluid velocity, across the whole fluid domain, is the same as the velocity at the interface. By an integration in time, we know that the displacements of the fluid particles $\xi(X, t) = d(X_1, t)$ are independent of X as well. Therefore, $x - x_1(t) = X - X_1$. Based on this relation, the solutions for the FSI equations (14) to (20) are summarised as follows:

$$d(X, t) = \frac{a}{\omega} \sin(\phi(X - X_0)) \sin(\omega t), \quad X \in [X_0, X_1]. \quad (27)$$

$$p(x(X, t), t) = \left[(X - X_1) \omega \rho^f a \sin(\phi(X_1 - X_0)) - \frac{a \phi(2\mu^s + \lambda^s)}{\omega} \cos(\phi(X_1 - X_0)) \right] \sin(\omega t), \quad (28)$$

$$u(x, t) = a \sin(\phi(X_1 - X_0)) \cos(\omega t), \quad x \in [X_1, X_2]. \quad (29)$$

The motion of the interface is included in the solution $d(X, t)$, i.e.: $X_1 + d(X_1, t)$. The boundary pressure is also included in the solution as:

$$\begin{aligned} \bar{p}(t) &= p(x_2(t), t) \\ &= \left[(X_2 - X_1) \omega \rho^f a \sin(\phi(X_1 - X_0)) - \frac{a \phi(2\mu^s + \lambda^s)}{\omega} \cos(\phi(X_1 - X_0)) \right] \sin(\omega t), \end{aligned} \quad (30)$$

which is periodic in time with a frequency of ω .

3.2. Numerical validation

In this section we validate the analytical solutions derived in the previous section, using the one-velocity FSI method as described in Appendix A. The implementation is based on FreeFem++ [69], using the parameter set in Table 1 as an example, for which the maximal solid displacement is around 5% = 0.05/($X_1 - X_0$) of the width of the solid domain.

Remark 3. *The analytical solutions (27), (28), and (29) hold for solid deformations larger than 5%, despite Lamé's equation (3) assuming small displacements in physics. However, the numerical simulation becomes challenging due the moving mesh, and also because one has to make sure the vertical components of the velocity and displacement are always numerically negligible.*

ρ^f	ρ^s	μ^f	μ^s	λ^s	X_0	X_1	X_2	ϕ	a
1	2	2	10	100	3	4	5	1.75π	2

Table 1: A group of parameters for the compressed parallel plates.

We consider computation domain of a $\Omega_1 = (X_2 - X_0) \times H = 2 \times 4$ rectangle and apply a periodic boundary at the top and bottom boundaries. We start from a relative coarse mesh with 861 nodes and 1600 triangles as shown in Figure 3, and a time step of $\Delta t = 10^{-3}$ to compute up to a time of $T_1 = 0.5$ which is more than 3 time periods of oscillations.

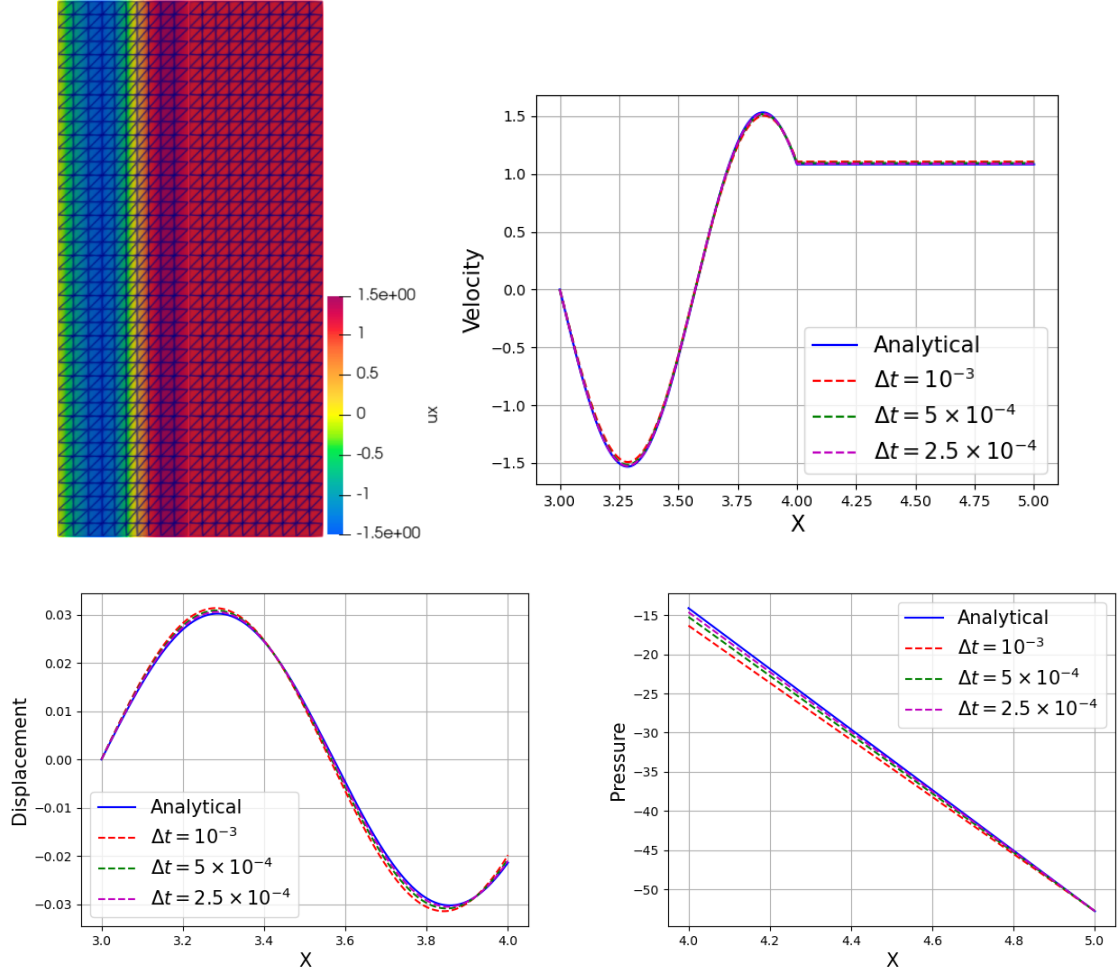


Figure 3: Diagram showing the numerical result as well as its comparison with the analytical solutions at $t = 0.5$: from left to right and top to bottom, horizontal velocity on a coarse mesh, comparisons of the velocity, displacement and pressure.

All the numerical results of velocity, pressure and displacement already agree well with our analytical solutions on this coarse mesh as shown in Figure 3, although we observe that the errors increase gradually as time evolves.

205 Based on the coarse mesh (Figure 3) and $\Delta t = 10^{-3}$, we refine the mesh and reduce the time step to test the spatiotemporal convergence of the numerical methods using $L^2([0, T_1]; L^2(\Omega_1))$ norm: first compute the $L^2(\Omega_1)$ error given a specific time, denoted by $e(t)$, then compute $L^2([0, T_1])$ norm of $e(t)$. We use a backward Euler scheme for the time discretisation and P_2P_1 element for the space discretisation of the velocity-pressure pair.
 210 The optimal spatiotemporal convergence is achieved as shown in Figure 4.

Remark 4. *There is a special case when $\phi(X_1 - X_0) = n\pi$ with $n \in \mathbb{N}$, in which $u(x, t) \equiv 0$. This means the entire fluid remains stationary, while a compressed solid wave oscillates across $[X_0, X_1]$, with the boundary pressure $\bar{p}(t)$ passing through the fluid and directly acting on the solid. Please refer to Appendix Appendix B.1 for a brief test of this case and the*
 215 *supporting animations at <https://yongxingwang.github.io/simulation/>.*

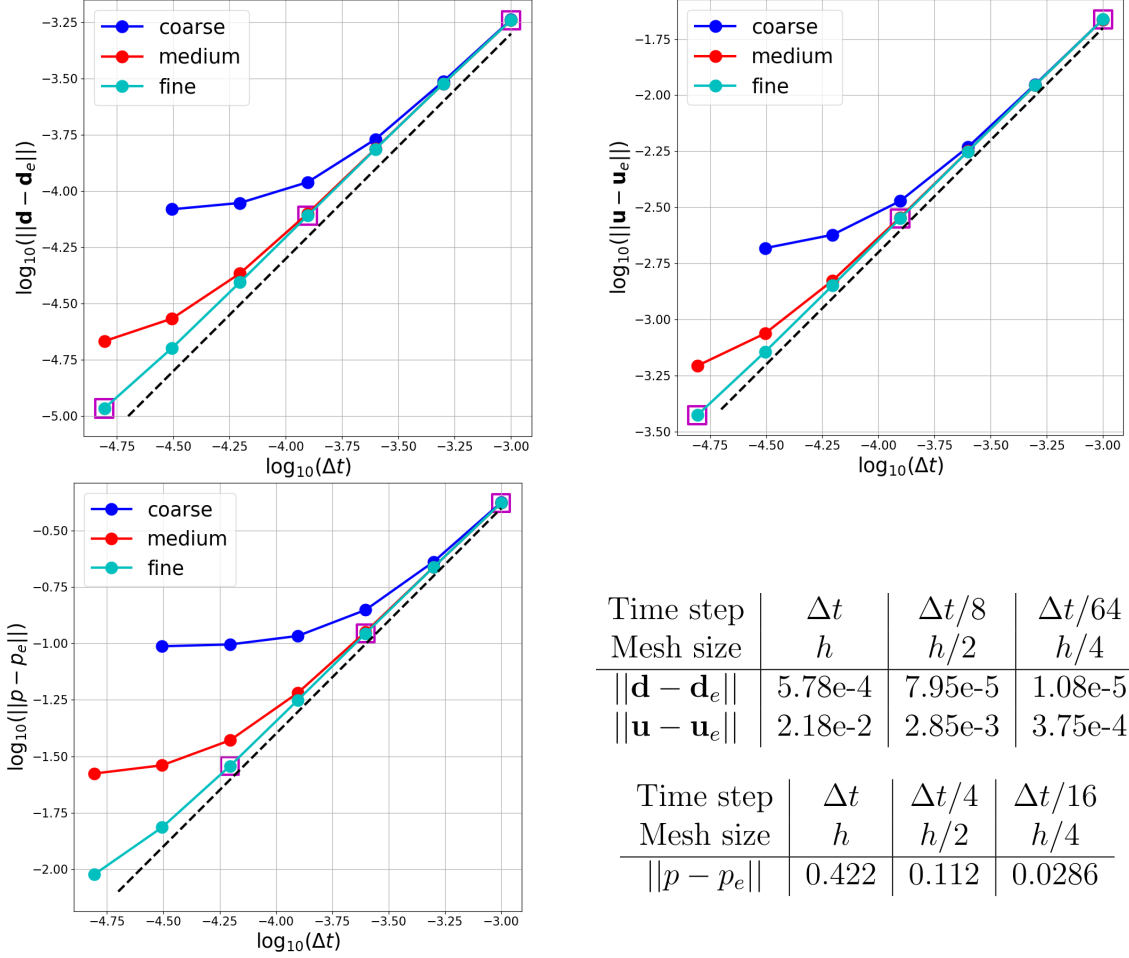


Figure 4: Spatiotemporal convergence of the displacement, velocity and pressure in space $L^2([0, T_1]; L^2(\Omega_1))$, where Ω_1 is the reference computational domain at $t = 0$. The two tables show the errors corresponding to the squared points in the graphs, which indicate the optimal convergence of backward Euler and P_2P_1 element for the time and the space discretisations respectively. The size of the coarse mesh is $h = 0.1$ and the initial time step $\Delta t = 10^{-3}$.

4. Problem II: compressed concentric discs

In this case, both the fluid velocity and the solid displacement only have components along the radial direction: $\mathbf{u} = u\mathbf{e}_r$ and $\mathbf{d} = d\hat{\mathbf{e}}_r$. Additionally, both $u = u(r, t)$ and $d = d(R, t) = r - R$ are independent of $\theta = \hat{\theta}$, and the pressure $p = p(r, t)$ is also independent of θ (or $\hat{\theta}$). Let $u' = \partial_r u$ and $p' = \partial_r p$ for notation convenience.

4.1. Fluid equations

Noticing that $\dot{\mathbf{e}}_r = \dot{\theta}\mathbf{e}_\theta = (u_\theta/r)\mathbf{e}_\theta = 0$, the inertial term can be expressed as:

$$\dot{\mathbf{u}} = \frac{d}{dt}(u_r\mathbf{e}_r) = \dot{u}\mathbf{e}_r = (\partial_t u + uu')\mathbf{e}_r. \quad (31)$$

Applying operator $\nabla \cdot \nabla$ to $\mathbf{u} = u_r\mathbf{e}_r$, we have

$$\nabla \cdot \nabla \mathbf{u} = (u'' + u'/r - u/r^2)\mathbf{e}_r. \quad (32)$$

These then yield the momentum equation

$$\rho^f(\partial_t u + uu') = \mu^f(u'' + u'/r - u/r^2) - p', \quad (33)$$

225 by substituting equations (31) and (32) into (1).

The continuity equation (2) becomes:

$$\nabla \cdot \mathbf{u} = \left(\mathbf{e}_r \partial_r + \frac{1}{r} \mathbf{e}_\theta \partial_\theta \right) \cdot (u \mathbf{e}_r) = \partial_r u + \frac{u}{r} = \frac{(ru)'}{r} = 0. \quad (34)$$

Finally, equation (34) may be substituted into equation (33) to obtain a simplified form of the momentum equation:

$$\rho^f(\partial_t u + uu') + p' = \mu^f(u' + \frac{u}{r})' = 0. \quad (35)$$

4.2. Solid equations

230 Apply the operators $\hat{\nabla}$ and $\hat{\nabla} \cdot \hat{\nabla}$ to the displacement vector, and let $d' = \partial_R d$, then

$$\hat{\nabla} \mathbf{d} = \left(\hat{\mathbf{e}}_r \partial_R + \frac{1}{R} \hat{\mathbf{e}}_\theta \partial_{\hat{\theta}} \right) (d \hat{\mathbf{e}}_r) = d' \hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + \frac{d}{R} \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_\theta, \quad (36)$$

$$\hat{\nabla}^\top \mathbf{d} = d' \hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + \frac{d}{R} \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_\theta = \hat{\nabla} \mathbf{d}, \quad (37)$$

$$\hat{\nabla} \cdot \hat{\nabla} \mathbf{d} = (d'' + d'/R - d/R^2) \hat{\mathbf{e}}_r. \quad (38)$$

Similar to the continuity equation of the fluid,

$$\hat{\nabla} \cdot \mathbf{d} = \left(\hat{\mathbf{e}}_r \partial_R + \frac{1}{R} \hat{\mathbf{e}}_\theta \partial_{\hat{\theta}} \right) \cdot (d \hat{\mathbf{e}}_r) = d' + \frac{d}{R}, \quad (39)$$

which however is not zero. Instead, applying the Nabla operator (11) to $\hat{\nabla} \cdot \mathbf{d}$, we have

$$\hat{\nabla}(\hat{\nabla} \cdot \mathbf{d}) = \left(\hat{\mathbf{e}}_r \partial_R + \frac{1}{R} \hat{\mathbf{e}}_\theta \partial_{\hat{\theta}} \right) \left(d' + \frac{d}{R} \right) = (d' + d/R)' \hat{\mathbf{e}}_r. \quad (40)$$

235 Finally, substituting equations (38) and (40) into the solid equation (3), we obtain

$$\rho^s \ddot{d} = (2\mu^s + \lambda^s) (d' + d/R)'. \quad (41)$$

4.3. Boundary conditions

As discussed in Section 3, the fluid equation (35) is expressed in the current or physical domain corresponding to the reference domain $[R_1, R_2]$, while the solid equation (41) is expressed directly in the reference domain $[R_0, R_1]$. We use the Lagrangian mapping to find
 240 the current domain for the fluid, i.e., extending the solid displacement $d(R, t)$ ($R \in [R_0, R_1]$) to the displacement of the fluid particles $\xi(R, t)$ ($R \in [R_1, R_2]$), with $\xi(R_1, t) = d(R_1, t)$ at

the interface. Let $r_1(t) = R_1 + \xi(R_1, t)$ and $r_2(t) = R_2 + \xi(R_2, t)$, then $r(R, t) = R + \xi(R, t)$ with $R \in [R_1, R_2]$ represents a general point in the current domain $[r_1(t), r_2(t)]$.

245 With the above notations, the continuity of normal stress at $R = R_1$ or $r = r_1(t)$ requires that:

$$\mu^s \left(\hat{\nabla} \mathbf{d} + \hat{\nabla}^\top \mathbf{d} \right) \cdot \hat{\mathbf{e}}_r + \lambda^s \left(\hat{\nabla} \cdot \mathbf{d} \right) \mathbf{I} \cdot \hat{\mathbf{e}}_r = \mu^f \left(\nabla \mathbf{u} + \nabla^\top \mathbf{u} \right) \cdot \mathbf{e}_r - p \mathbf{I} \cdot \mathbf{e}_r, \quad (42)$$

or equivalently,

$$\begin{aligned} & 2\mu^s \left(d'(R_1, t) \hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + \frac{d(R_1, t)}{R_1} \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_\theta \right) \cdot \hat{\mathbf{e}}_r + \lambda^s \left(d'(R_1, t) + \frac{d(R_1, t)}{R_1} \right) (\hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_\theta) \cdot \hat{\mathbf{e}}_r \\ & = \mu^f \left(u'(r_1, t) \mathbf{e}_r \mathbf{e}_r + \frac{u(r_1, t)}{r_1(t)} \mathbf{e}_\theta \mathbf{e}_\theta \right) \cdot \mathbf{e}_r - p(r_1, t) (\mathbf{e}_r \mathbf{e}_r + \mathbf{e}_\theta \mathbf{e}_\theta) \cdot \mathbf{e}_r. \end{aligned} \quad (43)$$

\Rightarrow

$$2\mu^s d'(R_1, t) + \lambda^s \left(d'(R_1, t) + \frac{d(R_1, t)}{R_1} \right) = \mu^f u'(r_1, t) - p(r_1, t). \quad (44)$$

Other boundary conditions include:

$$d(R_0, t) = 0 \quad (45)$$

$$\dot{d}(R_1, t) = u(r_1(t), t) \quad (46)$$

$$\mu^f u'(r_2, t) - p(r_2, t) = \bar{p}(t) \quad (47)$$

where (47) specifies the normal stress at the outer fluid boundary.

250 4.4. Analytical solution

Assuming the solution of equation (41) is periodic and separable with respect to R and t , then it can be represented by the real or imaginary part of a complex form: $d(R, t) = z(R)e^{i\omega t}$. This representation enables us to derive the equation for $d(R)$ by substituting $z(R)e^{i\omega t}$ into (41), yielding:

$$-\rho^s \omega^2 z = (2\mu^s + \lambda^s) (z'' + z'/R - z/R^2). \quad (48)$$

255 Let $\sqrt{\rho^s \omega^2 / (2\mu^s + \lambda^s)} = k^s$, the above equation can be rewritten as:

$$R^2 z'' + R z' + [(k^s R)^2 - 1] z = 0. \quad (49)$$

By change of variable: $k^s R = x$, the above equation becomes the Bessel's ODE of order one.

$$x^2 \frac{d^2 z}{dx^2} + x \frac{dz}{dx} + (x^2 - 1) z = 0, \quad (50)$$

with a general solution

$$z(R(x)) = c_1 J_1(x) + c_2 Y_1(x), \quad (51)$$

where $J_1(x)$ and $Y_1(x)$ are the first and second kind Bessel functions, respectively, of order one as follows:

$$J_1(x) = \sum_{m=0}^{\infty} \frac{(-1)^m}{m!(m+1)!} \left(\frac{x}{2}\right)^{2m+1}, \quad (52)$$

$$\frac{\pi}{2}Y_1(x) = \left(\gamma + \ln \frac{x}{2}\right) J_1(x) - \frac{1}{x} + \frac{1}{2} \sum_{m=1}^{\infty} \frac{(-1)^m (H_{m-1} + H_m)}{(m-1)!m!} \left(\frac{x}{2}\right)^{2m-1}. \quad (53)$$

with $H_0 = 0$, $H_m = 1 + 1/2 + 1/3 + \dots + 1/m$ and $\gamma = \lim_{m \rightarrow \infty} (H_m - \ln m)$. The solution of equation (49) can then be expressed as:

$$z(R) = c_1 J_1(k^s R) + c_2 Y_1(k^s R), \quad (54)$$

with the constants c_1 and c_2 being determined by the boundary conditions later. Let the $d(R, t) = z(R) \sin(\omega t)$ being the solution of (41), we derive the solution of fluid equations (34) and (35) as follows:

First, the continuity equation (34) indicates that ru is a constant: independent of r but possibly dependent of t . Recall the mapping between $r \in [r_1(t), r_2(t)]$ and $R \in [R_1, R_2]$: $r(R, t) = R + \xi(R, t)$, we have

$$ru = (R_1 + d(R_1, t)) \dot{d}(R_1, t), \quad (55)$$

due to the interface condition (46). This solves for the fluid velocity as:

$$u(r, t) = \frac{[R_1 + z(R_1) \sin(\omega t)] z(R_1) \omega \cos(\omega t)}{r}. \quad (56)$$

Notice that the initial condition of the velocity is determined the expression in (56), which cannot be zero generally, although the initial condition for the displacement is zero. The pressure can then be solved by the momentum equation (35)

$$p'(r, t) = \frac{z(R_1) \rho^f \omega^2 [R_1 \sin(\omega t) - z(R_1) \cos(2\omega t)]}{r} - \rho^f \frac{(u^2)'}{2} \quad (57)$$

Integrate to obtain the expression of $p(x, t)$:

$$p(r, t) = z(R_1) \rho^f \omega^2 [R_1 \sin(\omega t) - z(R_1) \cos(2\omega t)] \ln |r| - \rho^f \frac{u^2(r, t)}{2} + p^0(t). \quad (58)$$

The constant p^0 can be computed using the continuity of normal stress at the interface (44):

$$(2\mu^s + \lambda^s) z'(R_1) \sin(\omega t) + \lambda^s z(R_1) \sin(\omega t) / R_1 = \mu^f u'(r_1, t) - p(r_1, t), \quad (59)$$

\Rightarrow

$$\begin{aligned} -p^0(t) &= (2\mu^s + \lambda^s) z'(R_1) \sin(\omega t) + \lambda^s z(R_1) \sin(\omega t) / R_1 \\ &\quad + \frac{\mu^f z(R_1) \omega \cos(\omega t)}{r_1(t)} - \rho^f \frac{u^2(r_1(t), t)}{2} \\ &\quad + z(R_1) \rho^f \omega^2 [R_1 \sin(\omega t) - z(R_1) \cos(2\omega t)] \ln |r_1(t)| \end{aligned} \quad (60)$$

Substituting (60) into (58), we have

$$\begin{aligned}
p(r, t) = & z(R_1)\rho^f\omega^2 [R_1 \sin(\omega t) - z(R_1) \cos(2\omega t)] \ln \left| \frac{r}{r_1(t)} \right| \\
& - \rho^f \frac{u^2(r, t) - u^2(r_1(t), t)}{2} - \frac{\mu^f z(R_1)\omega \cos(\omega t)}{r_1(t)} \\
& - (2\mu^s + \lambda^s)z'(R_1) \sin(\omega t) - \lambda^s z(R_1) \sin(\omega t)/R_1,
\end{aligned} \tag{61}$$

where $r_1(t) = R_1 + z(R_1) \sin(\omega t)$.

Finally, the two constants c_1 and c_2 in the expression of $z(R)$ can be determined by two boundary conditions: (45) $\Rightarrow z(R_0) = 0$ and (47) $\Rightarrow p(r_2, t) = \mu^f u'(r_2, t) - \bar{p}(t)$, given $\bar{p}(t)$. However, because of the complicated form of $p(r, t)$, it is difficult to solve for $z(R_1)$ from the second condition. We simply specify $z(R_1)$ as \bar{d} – the largest displacement at R_1 , to determine the constants c_1 and c_2 first, and then write down the expression of $\bar{p}(t)$ for the problem. To express c_1 and c_2 explicitly, we have the linear system

$$z(R_0) = J_1(k^s R_0)c_1 + Y_1(k^s R_0)c_2 = 0, \tag{62}$$

$$z(R_1) = J_1(k^s R_1)c_1 + Y_1(k^s R_1)c_2 = \bar{d}, \tag{63}$$

whose solution can be expressed as:

$$\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \frac{1}{\det} \begin{pmatrix} Y_1(k^s R_1) & -Y_1(k^s R_0) \\ -J_1(k^s R_1) & J_1(k^s R_0) \end{pmatrix} \begin{pmatrix} 0 \\ \bar{d} \end{pmatrix}, \tag{64}$$

where $\det = J_1(k^s R_0)Y_1(k^s R_1) - J_1(k^s R_1)Y_1(k^s R_0)$.

Remark 5. *To accurately evaluate Bessel functions is not trivial, especially for large arguments. Classically, power series are used for small arguments and asymptotic series for large arguments. Nonlinear sequence transformations are employed for intermediate arguments to bridge the gap between the asymptotic expansion for large arguments and the Taylor expansion for small arguments [70, 71]. Additionally, methods such as integral representation with the trapezoidal rule are adopted to compute Bessel functions [72–74]. Our implementation in this article is based on the scipy.special library [75].*

4.5. Mapping between r and R

Since the solutions of fluid and solid are expressed in different configurations. In order to display and visualise results, such as showing the velocity of both the fluid and solid across $[R_0, R_2]$, it is necessary to write down the mapping between r and R explicitly. For $R \in [R_0, R_1]$, $r = R + z(R) \sin(\omega t)$; for $R \in [R_1, R_2]$, the mapping can be computed by solving equation (55):

$$ru = \frac{d}{dt} \left(\frac{r^2(R, t)}{2} \right) = (R_1 + z(R_1) \sin(\omega t)) z(R_1) \omega \cos(\omega t) \tag{65}$$

$$\Rightarrow \frac{r^2(R, t)}{2} = R_1 z(R_1) \sin(\omega t) + \int z^2(R_1) \frac{\omega \sin(2\omega t)}{2} dt \quad (66)$$

$$\Rightarrow \frac{r^2(R, t)}{2} = R_1 z(R_1) \sin(\omega t) - z^2(R_1) \frac{\cos(2\omega t)}{4} + C(R). \quad (67)$$

Since $r(R, 0) = R \Rightarrow C(R) = R^2/2 + z^2(R_1)/4$, therefore,

$$\frac{r^2(R, t)}{2} = R_1 z(R_1) \sin(\omega t) + z^2(R_1) \frac{\sin^2(\omega t)}{2} + \frac{R^2}{2}. \quad (68)$$

$$\Rightarrow r^2(R, t) = R^2 + (R_1 + z(R_1) \sin(\omega t))^2 - R_1^2, \quad (69)$$

305 which is the relation between r and R .

Remark 6. Equation (41) possesses another form of solution: $d(R, t) = z(R)t$, where $z(R) = C_1 R + R/C_2$ represents the steady-state solution for (41) – an Euler PDE, with C_1 and C_2 being two constants. Consequently, this would yield an alternative solution for the FSI problem, albeit with distinct boundary conditions.

310 4.6. Numerical validation

We validate the analytical solutions of the solid displacement $d(R, t) = z(R) \sin(\omega t)$ as well as its velocity $u(R, t) = z(R) \omega \cos(\omega t)$, together with the fluid velocity (56) and pressure (61), against the results of two-dimensional numerical simulations. We compare all the quantities in the reference configuration based on the mapping as described in Section 4.5: the results for a typical parameter set shown in Table 2. We set $z(R_1) = \bar{d} = 0.05$ to compute the coefficients c_1 and c_2 in (63), which is $\bar{d}/(R_1 - R_0) = 5\%$ of deformation of the width of the solid domain.

ρ^f	ρ^s	μ^f	μ^s	λ^s	R_0	R_1	R_2	ω
1	2	2	10	100	3	4	5	2π

Table 2: A group of parameters for the compressed disc.

It can be seen in Figure 6 how the simulation results, based on a relatively coarse mesh (see Figure 5), converge to the analytical solution over time. The evolution of the fluid-solid interface is plotted in Figure 7, from which it can be observed that the error gradually increases as time progresses. The results of spatiotemporal convergence are displayed in Figure 8, with the last figure (bottom-right) showing the time convergence of the $L^2(\Omega_2)$ error at $T_2 = 0.5$ on the medium mesh. We find that the time convergence rate is not optimal; this is because there is an accumulated error when comparing the last figure (bottom-right) in Figure 8 to the other three. The accumulated error may be due to our implementation of the Bessel functions and the data transfer between Python and FreeFem++, which needs further investigations. The lack of optimal mesh convergence is understandable because

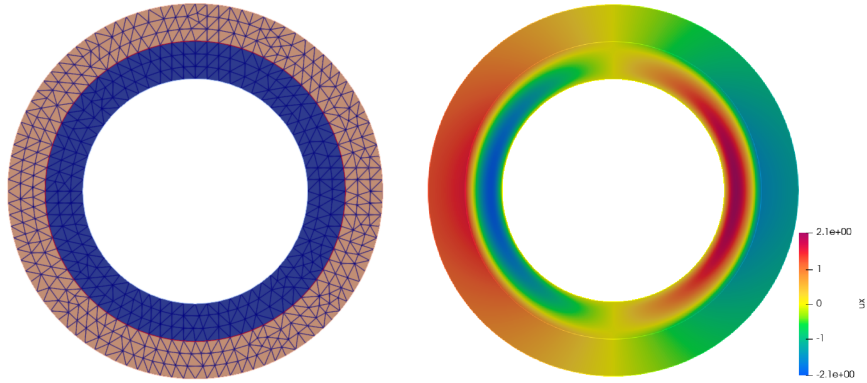


Figure 5: A coarse mesh with 572 nodes and 1225 triangle (left), and the horizontal velocity profile at $t = 0.5$ (right).

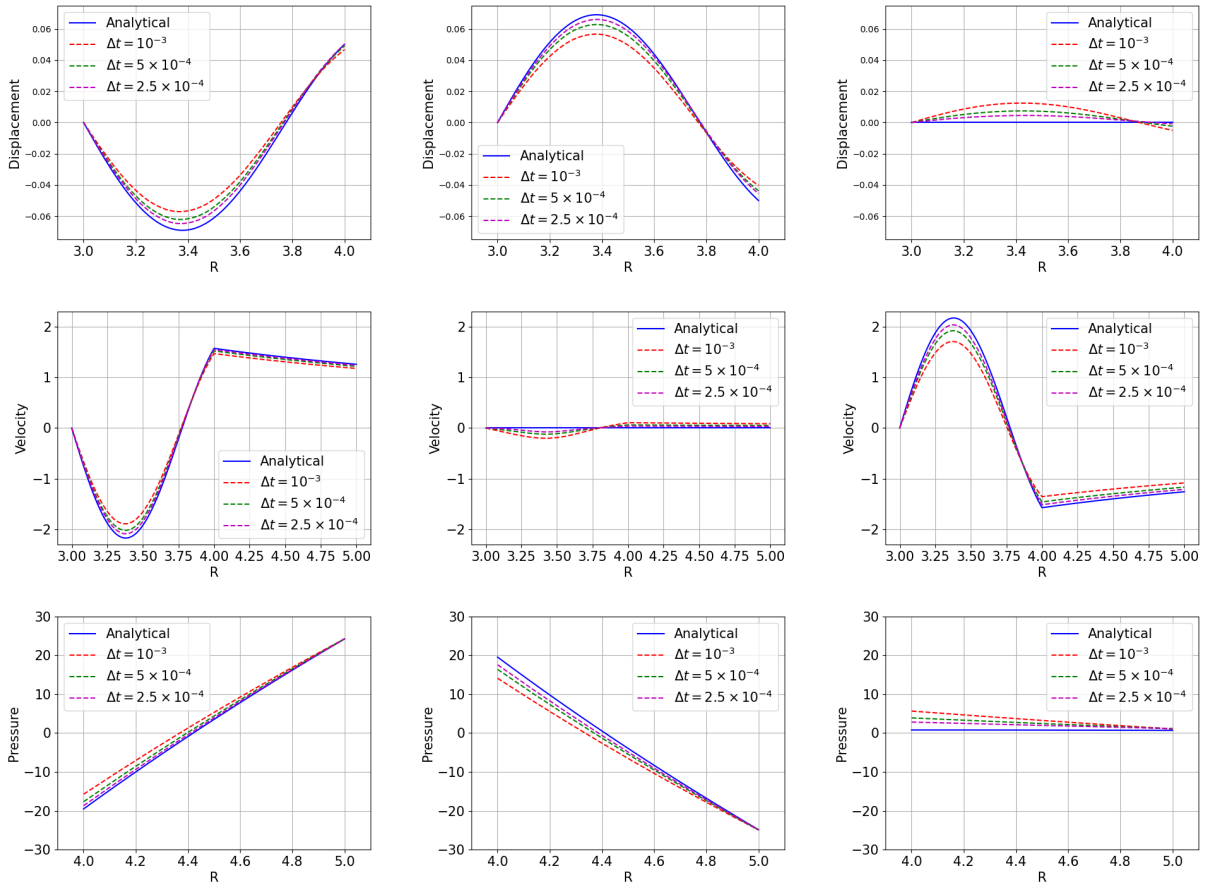


Figure 6: Comparison of displacement (first row), velocity (second row), pressure (third row) at three at $t = 0.25$, $t = 0.35$ and $t = 0.5$ from left to right, except the plot of velocity at the second row and first column which is at $t = 0.2$, because the velocity profile at $t = 0.25$ is very similar to $t = 0.35$.

FreeFem++ does not use isoparametric mesh for P_2P_1 elements. Our focus here is on validating the analytical solution, leaving the testing of the convergence rate of the numerical scheme for future study.

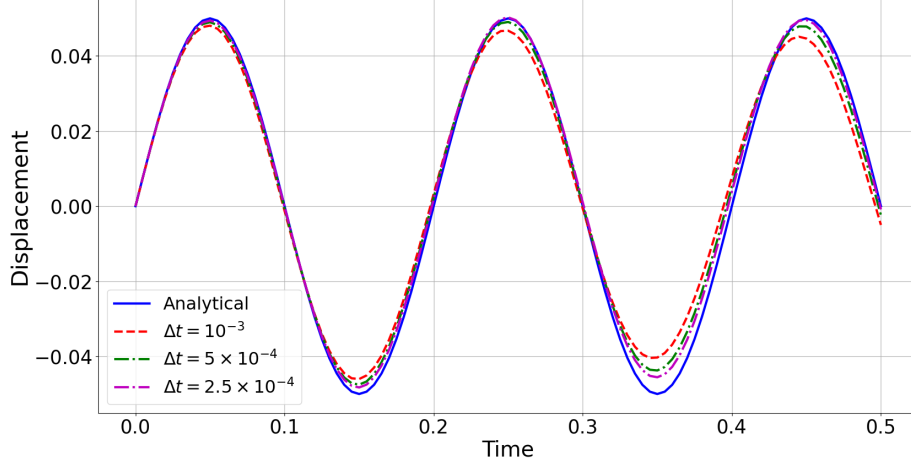


Figure 7: Displacement of the interface as a function of time.

Remark 7. *This problem can pose significant challenges for numerical simulations when moving the mesh, particularly when multiple compression waves propagate within the solid. For instance, setting $R_0 = 1$ in the parameter set outlined in Table 2 and $\bar{d} = 0.15$ (equivalent to 5% of the width of the solid domain $R_1 - R_0$) results in the emergence of a rapidly propagating wave within the solid, as illustrated in Figure B.12.*

335

5. Problem III: rotating concentric discs

We assume pure rotation for this problem. For the fluid, the velocity vector $\mathbf{u} = u\mathbf{e}_\theta$ only has the tangential component $u = u(r, t)$, which is independent of θ . The pressure $p = p(r, t)$ is also independent of θ . For the solid, pure rotation means $r = R$ is independent of time in the position vector $r\mathbf{e}_r$, so its velocity, $\frac{d}{dt}(r\mathbf{e}_r) = r\dot{\theta}\mathbf{e}_\theta$, only has the tangential component. Assuming the angular displacement $\alpha = \theta - \hat{\theta} = \alpha(r, t)$ is independent of $\hat{\theta}$, then $\theta = \alpha + \hat{\theta}$, $\partial_r\theta = \partial_r\alpha$, and $\partial_{\hat{\theta}}\theta = 1$, which will be used in the following derivations. Finally, let $\dot{u} = \frac{du}{dt}$, $\dot{\alpha} = \frac{d\alpha}{dt}$, $u' = \partial_r u$, and $\alpha' = \partial_r \alpha$ for the convenience of notation.

340

5.1. Fluid equations

Since $\dot{\mathbf{e}}_\theta = -\dot{\theta}\mathbf{e}_r = -(u/r)\mathbf{e}_r$, the inertial term can be expressed as:

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$$\dot{\mathbf{u}} = \dot{u}\mathbf{e}_\theta - (u^2/r)\mathbf{e}_r. \quad (70)$$

Apply the Nabla operator to $\mathbf{u} = u\mathbf{e}_\theta$:

$$\nabla\mathbf{u} = \left(\mathbf{e}_r\partial_r + \mathbf{e}_\theta\frac{1}{r}\partial_\theta\right)(u\mathbf{e}_\theta) = \partial_r u\mathbf{e}_r\mathbf{e}_\theta - \frac{1}{r}u\mathbf{e}_\theta\mathbf{e}_r, \quad (71)$$

$$\nabla \cdot \nabla\mathbf{u} = \left(\partial_{rr} + \frac{1}{r}\partial_r + \frac{1}{r^2}\partial_{\theta\theta}\right)(u\mathbf{e}_\theta) = \left(\partial_{rr}u + \frac{1}{r}\partial_r u_\theta - \frac{u}{r^2}\right)\mathbf{e}_\theta. \quad (72)$$

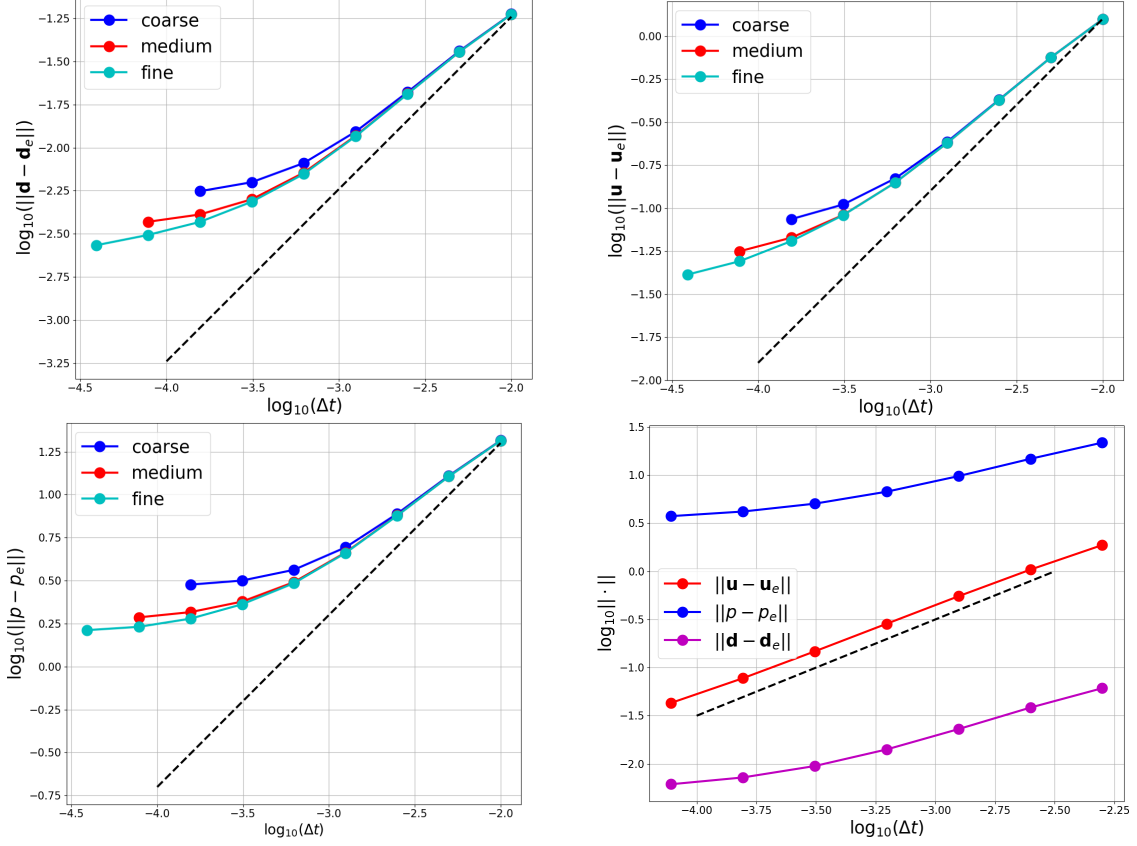


Figure 8: From left to right and top to bottom, the first three plots are spatiotemporal convergence of the displacement, velocity and pressure in space $L^2([0, T_2]; L^2(\Omega_2))$, where $T_2 = 0.5$, and Ω_2 is the reference computational domain at $t = 0$. The last plot is the time convergence of the $L^2(\Omega_2)$ error of the velocity, displacement and pressure at $T_2 = 0.5$ on the medium mesh. The mesh size is defined by the maximum size of the elements.

$$\nabla p^f = \left(\mathbf{e}_r \partial_r + \mathbf{e}_\theta \frac{1}{r} \partial_\theta \right) p = \partial_r p^f \mathbf{e}_r. \quad (73)$$

The continuity equation (2) is automatically satisfied since

$$\nabla \cdot \mathbf{u} = \left(\mathbf{e}_r \partial_r + \frac{1}{r} \mathbf{e}_\theta \partial_\theta \right) \cdot (u \mathbf{e}_\theta) = 0. \quad (74)$$

Combining the above equations(70), 72) and (73), the momentum equation (1) can be expressed, in the polar coordinate system, as:

$$\rho^f \dot{u} = \mu^f (u'' + u'/r - u/r^2), \quad (75)$$

and

$$-\rho^f u^2/r = -\partial_r p^f. \quad (76)$$

5.2. Solid equations

We use a large displacement formulation of an incompressible Neo-Hookean solid model. We apply the Nabla operator $\hat{\nabla}$ to the position vector $r\mathbf{e}_r$ to compute the deformation tensor:

$$\mathbf{F} = \hat{\nabla}(r\mathbf{e}_r) = \left(\hat{\mathbf{e}}_r \partial_R + \frac{1}{R} \hat{\mathbf{e}}_\theta \partial_{\hat{\theta}} \right) (r\mathbf{e}_r) = \hat{\mathbf{e}}_r \mathbf{e}_r + \hat{\mathbf{e}}_r \mathbf{e}_\theta (r\theta') + \hat{\mathbf{e}}_\theta \mathbf{e}_\theta, \quad (77)$$

due to $\partial_R \mathbf{e}_r = \mathbf{e}_\theta \partial_R \theta = \mathbf{e}_\theta \theta'$ and $\partial_{\hat{\theta}} \mathbf{e}_r = \mathbf{e}_\theta \partial_{\hat{\theta}} \theta = \mathbf{e}_\theta$. Then,

$$\begin{aligned} \mathbf{F}\mathbf{F}^\top &= (\hat{\mathbf{e}}_r \mathbf{e}_r + \hat{\mathbf{e}}_r \mathbf{e}_\theta (r\theta') + \hat{\mathbf{e}}_\theta \mathbf{e}_\theta) \cdot (\mathbf{e}_r \hat{\mathbf{e}}_r + \mathbf{e}_\theta \hat{\mathbf{e}}_r (r\theta') + \mathbf{e}_\theta \hat{\mathbf{e}}_\theta) \\ &= [1 + (r\theta')^2] \hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + (r\theta') \hat{\mathbf{e}}_r \hat{\mathbf{e}}_\theta + (r\theta') \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_r + \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_\theta, \end{aligned} \quad (78)$$

and further

$$\mathbf{F}\mathbf{F}^\top - \mathbf{I} = (r\theta')^2 \hat{\mathbf{e}}_r \hat{\mathbf{e}}_r + (r\theta') \hat{\mathbf{e}}_r \hat{\mathbf{e}}_\theta + (r\theta') \hat{\mathbf{e}}_\theta \hat{\mathbf{e}}_r. \quad (79)$$

In the spirit of expressing the solid equation in the current configuration, we replace $(\hat{\mathbf{e}}_r, \hat{\mathbf{e}}_\theta)$ by $(\mathbf{e}_r, \mathbf{e}_\theta)$ in equation (79) using the relation (12):

$$\mathbf{F}\mathbf{F}^\top - \mathbf{I} = \tau_{11} \mathbf{e}_r \mathbf{e}_r + \tau_{22} \mathbf{e}_\theta \mathbf{e}_\theta + \tau_{12} \mathbf{e}_\theta \mathbf{e}_r + \tau_{21} \mathbf{e}_r \mathbf{e}_\theta, \quad (80)$$

with $\tau_{11} = (r\alpha')^2 \cos^2 \alpha + (r\alpha') \sin(2\alpha)$, $\tau_{22} = (r\alpha')^2 \sin^2 \alpha - (r\alpha') \sin(2\alpha)$ and $\tau_{12} = \tau_{21} = (r\alpha') \cos(2\alpha) - \frac{(r\alpha')^2}{2} \sin(2\alpha)$, noticing that $\theta' = \alpha'$. We then have

$$\nabla \cdot (\mathbf{F}\mathbf{F}^\top - \mathbf{I}) = \partial_r \tau_{12} \mathbf{e}_\theta + \frac{2\tau_{12}}{r} \mathbf{e}_\theta + \partial_r \tau_{11} \mathbf{e}_r + \frac{\tau_{11} - \tau_{22}}{r} \mathbf{e}_r. \quad (81)$$

The inertial term is

$$\ddot{\mathbf{d}} = \frac{d^2}{dt^2}(r\mathbf{e}_r) = \frac{d}{dt}(r\dot{\alpha}\mathbf{e}_\theta) = r\ddot{\alpha}\mathbf{e}_\theta - r\dot{\alpha}^2\mathbf{e}_r, \quad (82)$$

bearing in mind that $\dot{\theta} = \dot{\alpha}$.

Substituting equations (81) and (82) into the solid equation (4), we have

$$\rho^s r \ddot{\alpha} = \mu^s [\partial_r \tau_{12} + 2\tau_{12}/r], \quad (83)$$

and

$$-\rho^s r \dot{\alpha}^2 = \mu^s [\partial_r \tau_{11} + (\tau_{11} - \tau_{22})/r] - \partial_r p^s. \quad (84)$$

5.3. Boundary and initial conditions

The continuity of normal stress at the interface $r = R_1$ indicates that:

$$\mu^s (\mathbf{F}\mathbf{F}^\top - \mathbf{I}) \cdot \mathbf{e}_r - p^s \mathbf{I} \cdot \mathbf{e}_r = \mu^f (\nabla^\top \mathbf{u} + \nabla \mathbf{u}) \cdot \mathbf{e}_r - p^f \mathbf{I} \cdot \mathbf{e}_r, \quad (85)$$

\Rightarrow

$$\mu^s (\tau_{11} \mathbf{e}_r + \tau_{12} \mathbf{e}_\theta) - p^s \mathbf{e}_r = \mu^f \left(u' - \frac{u}{r} \right) \mathbf{e}_\theta - p^f \mathbf{e}_r \quad \text{at } r = R_1. \quad (86)$$

⇒

$$\mu^s \tau_{12}(\alpha(R_1, t)) = \mu^f [u'(R_1, t) - u(R_1, t)/R_1] \quad (87)$$

$$\mu^s \tau_{11}(\alpha(R_1, t)) = p^s(R_1, t) - p^f(R_1, t) \quad (88)$$

Other boundary conditions include:

$$\alpha(R_0, t) = 0, \quad (89)$$

$$R_1 \dot{\alpha}(R_1, t) = u(R_1, t), \quad (90)$$

$$u(R_2, t) = \bar{u}(t). \quad (91)$$

Initial conditions are:

$$\alpha(r, 0) = \alpha_0 \quad \text{in} \quad [R_0, R_1], \quad (92)$$

$$u(r, 0) = u_0 \quad \text{in} \quad [R_1, R_2]. \quad (93)$$

5.4. A one-velocity monolithic method

In this section, we use a finite element method to solve the velocity equation (75) of the fluid and the angular displacement equation (83) of the solid together in a fully-coupled manner. In addition, we express the angular displacement α in terms of velocity and only solve for one velocity field in domain $[R_0, R_2]$. For this method, the continuity of the velocity at the interface (90) is automatically satisfied. The pressure equations (76) and (84) are decoupled from the momentum equations, and will be solved as a postprocess.

Given a test function $v(r) \in H_0^1[R_0, R_2] = \{v : v \in H^1[R_0, R_2], v(R_0, t) = 0\}$, the weak form of (83) can be expressed as:

$$\rho^s \int_{R_0}^{R_1} r \ddot{\alpha} v dr = \mu^s \int_{R_0}^{R_1} \tau_{12}(\alpha) [2v/r - v'] dr + \mu^s \tau_{12}(\alpha(R_1, t)) v(R_1). \quad (94)$$

Considering the interface condition (87), the weak form of (75) may be expressed as:

$$\begin{aligned} \rho^f \int_{R_1}^{R_2} \dot{u} v &= \mu^f \int_{R_1}^{R_2} [(u' - u/r)' + 2(u'/r - u/r^2)] v dr \\ &= -\mu^f [u'(R_1, t) - u(R_1, t)/R_1] + \mu^f \int_{R_1}^{R_2} (u' - u/r)(2v/r - v') dr. \end{aligned} \quad (95)$$

The sum of equations (94) and (95) leads to the monolithic formulation as follows:

Given the initial values α_0 in (92) and u_0 in (93), find $u(r, t) \in H^1[R_0, R_2]$ such that $\forall v(r) \in H_0^1[R_0, R_2]$, the following equation holds:

$$\rho \int_{R_0}^{R_2} \dot{u} v dr = \mu^s \int_{R_0}^{R_1} \tau_{12}(\alpha) [2v/r - v'] dr + \mu^f \int_{R_1}^{R_2} (u' - u/r)(2v/r - v') dr, \quad (96)$$

where $\rho = \rho^s 1_{[R_0, R_1]} + \rho^f 1_{[R_1, R_2]}$ and $r \dot{\alpha} = u$ in $[R_0, R_1]$.

390 Function $\tau_{12}(\alpha)$ in (96) is non-linear in terms of α , we use the Newton method to linearise it as follows:

$$\tau_{12}(\alpha) \approx \tau_{12}(\alpha^k) + \delta\tau_{12}(\alpha^k; \alpha - \alpha^k), \quad (97)$$

where α^k is a reference point and $\delta\tau_{12}(\alpha; \beta)$ is the first order Gateaux variation at α along direction β [1, 76]:

$$\delta\tau_{12}(\alpha; \beta) = \left. \frac{d}{d\epsilon} \tau_{12}(\alpha + \epsilon\beta) \right|_{\epsilon=0}. \quad (98)$$

With this definition, we compute the variations of $\tau_{12}(\alpha)$:

$$\delta\tau_{12}(\alpha; \delta\alpha) = r\delta\alpha' \cos(2\alpha) - 2r\alpha' \sin(2\alpha)\delta\alpha - r^2\alpha' \sin(2\alpha)\delta\alpha' - (r\alpha')^2 \cos(2\alpha)\delta\alpha, \quad (99)$$

395 Substituting (99) into (97), with $\delta\alpha = \alpha - \alpha^k$, we have

$$\begin{aligned} \tau_{12}(\alpha) \approx & r\alpha' \cos(2\alpha^k) - 2r(\alpha^k)' \sin(2\alpha^k)(\alpha - \alpha^k) - r^2(\alpha^k)' \sin(2\alpha^k)(\alpha - \alpha^k)' \\ & - [r(\alpha^k)']^2 \cos(2\alpha^k)(\alpha - \alpha^k) - \frac{(r(\alpha^k)')^2}{2} \sin(2\alpha^k). \end{aligned} \quad (100)$$

Finally, we consider a linearisation in time. Given the previous values α_n and u_n at time t_n where $n = 0, 1, 2, \dots$, we use a uniform time step Δt to compute α_{n+1} and u_{n+1} . Since $r\dot{\alpha} = u$, we express $\alpha_{n+1} = \alpha_n + u_{n+1}\Delta t/r$ based on the backward Euler scheme. Dropping of the subscript $n + 1$ for convenience, and substituting $\alpha = \alpha_n + u\Delta t/r$ and
400 $\alpha' = \alpha'_n + \Delta t(u'/r - u/r^2)$, together with (100), to equation (96), we have the linearised one-velocity monolithic formulation after time discretisation:

Given α_n and u_n at time t_n , find $u_{n+1} = u(r, t) \in H^1[R_0, R_2]$ such that $\forall v(r) \in H_0^1[R_0, R_2]$, the following equation holds:

$$\begin{aligned} & \rho \int_{R_0}^{R_2} \frac{u - u_n}{\Delta t} v dr + \mu^f \int_{R_1}^{R_2} (u' - u/r)(v' - 2v/r) dr \\ & + \mu^s \int_{R_0}^{R_1} \Delta t [\cos(2\alpha^k) - r(\alpha^k)' \sin(2\alpha^k)] (u' - u/r)(v' - 2v/r) dr \\ & - \mu^s \int_{R_0}^{R_1} \Delta t [r((\alpha^k)')^2 \cos(2\alpha^k) + 2(\alpha^k)' \sin(2\alpha^k)] u(v' - 2v/r) dr \\ & = \mu^s \int_{R_0}^{R_1} [-r\alpha'_n \cos(2\alpha^k) + 2r(\alpha^k)' \sin(2\alpha^k) (\alpha_n - \alpha^k)] (v' - 2v/r) dr \\ & + \mu^s \int_{R_0}^{R_1} \left[r^2(\alpha^k)' \sin(2\alpha^k) (\alpha_n - \alpha^k)' + (r(\alpha^k)')^2 \cos(2\alpha^k) (\alpha_n - \alpha^k) \right] (v' - 2v/r) dr \\ & + \mu^s \int_{R_0}^{R_1} \frac{(r(\alpha^k)')^2}{2} \sin(2\alpha^k) (v' - 2v/r) dr. \end{aligned} \quad (101)$$

The pressure is computed as a post-process. Integration of equation (84) from R_0 to $R \in (R_0, R_1]$ yields the expression of the pressure of solid:

$$p^s(R, t) = \mu^s [\tau_{11}(\alpha(R)) - \tau_{11}(\alpha(R_0))] + \mu^s \int_{R_0}^R \frac{\tau_{11} - \tau_{22}}{r} dr + \rho^s \int_{R_0}^R \frac{u^2}{r} dr, \quad (102)$$

given a reference pressure $p^s(R_0, t) = 0$. Integration of equation (76) from R_1 to $R \in (R_1, R_2]$ yields the expression of the fluid pressure as follows:

$$p^f(R, t) = \rho^f \int_{R_1}^R \frac{u^2}{r} dr + p^f(R_1, t), \quad (103)$$

where $p^f(R_1, t) = p^s(R_1, t) - \mu^s \tau_{11}(\alpha(R_1))$ is known from the jump condition (88).

5.5. Numerical Validation

It is efficient to solve the one-dimensional problem (101) to very high accuracy, a solution we refer to as the semi-analytical solution. We tested a range of parameters and compared these semi-analytical solutions to those obtained from two-dimensional simulations using the numerical method described in Appendix A. We found that the one-dimensional and two-dimensional solutions agree very well. We report the results of the parameter set in Table 3, where a periodic boundary velocity profile is prescribed at boundary R_2 along the tangential direction: $\Omega(t) = \bar{u} \sin(\omega t)$ with $\bar{u} = 15$. Consequently, a complicated wave-like solution is created, and we have to use of a relatively fine mesh to capture this feature. A finite element mesh and the magnitude of the velocity at $t = 1$ are displayed in Figure 9 to visualise the wave pattern.

ρ^f	ρ^s	μ^f	μ^s	R_0	R_1	R_2	ω
1	2	2	10	3	4	5	10π

Table 3: A group of parameters for the rotating disc.

The comparison of displacement, velocity, and pressure between the 1D and 2D simulations is shown in Figure 10. It can be observed that the results for displacement and velocity agree well between the 1D and 2D simulations, while there is a discrepancy in pressure. We attribute this inconsistency in pressure to the discontinuity at $R = R_1$, which the P_2P_1 Taylor-Hood element cannot accurately capture, as can be seen in the last two plots of Figure 10. As a result, there is a shift in pressure within the fluid region, which consequently affects the accuracy of solid pressure as well.

6. Conclusion

In this paper, we propose three fluid-structure interaction problems and derive their analytical or semi-analytical solutions, which have been validated through numerical experiments. These FSI solutions fill the gap in the analytical solutions within the FSI community and contribute to the field by benchmarking numerical methods for FSI problems.

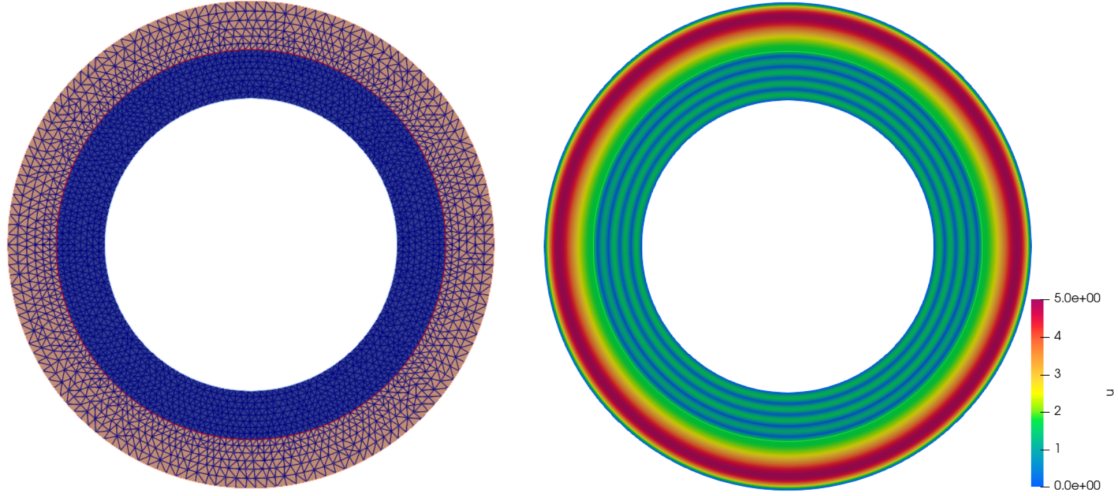


Figure 9: A coarse mesh with 2621 nodes and 5443 triangle and the magnitude of velocity profile at $t = 0.5$.

We also developed the one-velocity monolithic method to solve a one-dimensional non-linear problem (96) and an linear elastic problem in the reference domain (A.2). The one-velocity monolithic method is tested against the analytical solution, with results showing
435 good agreement between them.

The results between the analytical and numerical solutions for the rotating disc (Problem III) do not match very well, and we believe this is due to the pressure discontinuity across the fluid-solid interface not being captured accurately in the numerical methods. Different numerical strategies, such as discontinuous finite elements or regularisation methods, may
440 be explored in the future.

Appendix A. The one-velocity numerical methods for FSI problems

In this section, we briefly introduce the numerical method used to simulate two-dimensional problems. We employ the monolithic Eulerian method, as discussed in several references [58–60], to solve for a single velocity variable across the entire fluid-structure domain $\Omega_t^f \cup \Omega_t^s$.
445 Additionally, we utilise the arbitrary Lagrangian Eulerian method to handle the moving mesh.

Given the Cauchy stress tensor $\boldsymbol{\sigma}$ in the current configuration, the general weak form of this monolithic approach can be expressed as follows [60]:

$$\int_{\Omega} \rho (\partial_t \mathbf{u} + (\mathbf{u} - \mathbf{w}) \nabla \cdot \mathbf{u}) \delta \mathbf{u} + \int_{\Omega} \boldsymbol{\sigma} : \nabla \delta \mathbf{u} = \int_{\partial \Omega} (\boldsymbol{\sigma} \cdot \mathbf{n}) \cdot \delta \mathbf{u}, \quad (\text{A.1})$$

where $\rho = \rho^f 1_{\Omega^f} + \rho^s 1_{\Omega^s}$, $\boldsymbol{\sigma} = \boldsymbol{\sigma}^f 1_{\Omega^f} + \boldsymbol{\sigma}^s 1_{\Omega^s}$, \mathbf{w} is the prescribed mesh velocity, which
450 may be simply obtained by solving a static linear elastic equation, \mathbf{n} is the outer normal of domain Ω .

The one-velocity method aims to express the displacement $\mathbf{d}_{n+1} = \mathbf{d}_n + \Delta t \mathbf{u}_{n+1}$ after time discretisation, solving solely for the velocity \mathbf{u}_{n+1} at time t_{n+1} for the whole FSI problem,

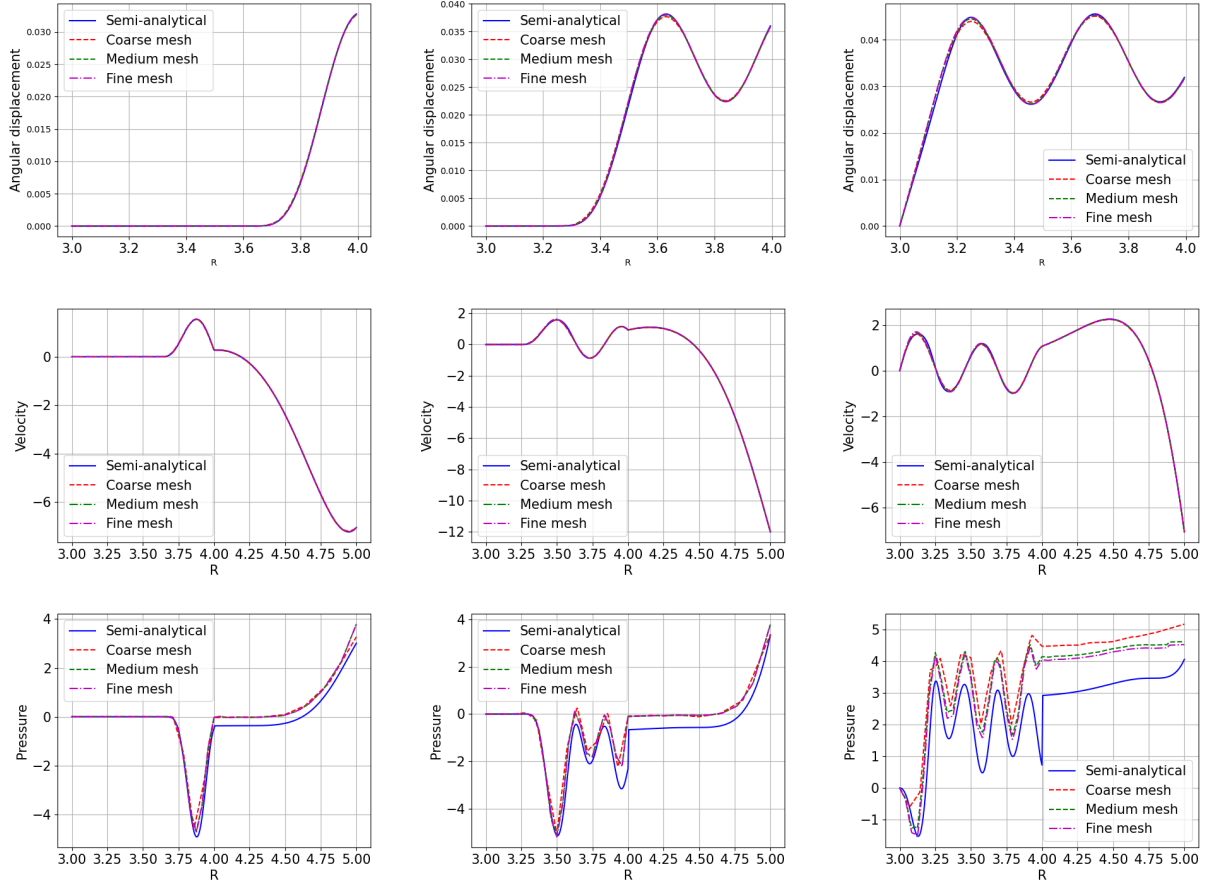


Figure 10: Comparison of angular displacement (first row), velocity (second row), and pressure (third row) at three time instances, $t = 0.2$, $t = 0.35$, and $t = 0.5$, from left to right. It is noteworthy that a maximum angular displacement of 0.045 corresponds to a maximum radial displacement of $0.045R_1 = 0.135$, which represents a 13.5% deformation of the width of the solid domain, $R_1 - R_0 = 1$.

given \mathbf{u}_n and \mathbf{d}_n at time t_n . The primary objective is then to express $\int_{\Omega} \boldsymbol{\sigma} : \nabla \delta \mathbf{u} = \int_{\Omega_t^f} \boldsymbol{\sigma}^f : \nabla \delta \mathbf{u} + \int_{\Omega_t^s} \boldsymbol{\sigma}^s : \nabla \delta \mathbf{u}$ in terms of displacement \mathbf{d} , which is discussed in the following.

The fluid integration expressions are the same for Problems I, II, and III: $\mathbf{d}_{n+1} = \mathbf{d}_n + \Delta t \mathbf{u}_{n+1}$ after time discretisation, and only solve for velocity \mathbf{u}_{n+1} at time t_{n+1} for the whole FSI problem, given \mathbf{u}_n and \mathbf{d}_n at time t_n . Then the main task is to express $\int_{\Omega} \boldsymbol{\sigma} : \nabla \delta \mathbf{u} = \int_{\Omega_t^f} \boldsymbol{\sigma}^f : \nabla \delta \mathbf{u} + \int_{\Omega_t^s} \boldsymbol{\sigma}^s : \nabla \delta \mathbf{u}$ in terms of displacement \mathbf{d} .

The fluid integration expressions are the same for Problems I, II, and III:

$$\int_{\Omega_t^f} \boldsymbol{\sigma}^f : \nabla \delta \mathbf{u} = \frac{\mu^f}{2} \int_{\Omega_t^f} (\nabla^{\top} \mathbf{u} + \nabla \mathbf{u}) : (\nabla^{\top} \delta \mathbf{u} + \nabla \delta \mathbf{u}) - \int_{\Omega_t^f} p \nabla \cdot \delta \mathbf{u}, \quad (\text{A.2})$$

but they differ in the boundary integration expression concerning the Neumann boundary condition: $\boldsymbol{\sigma} \cdot \mathbf{n} = \bar{p}(t) \mathbf{n}$ at boundary R_2 for Problem I and II, while $\boldsymbol{\sigma} \cdot \mathbf{n} = 0$ for Problem III. They also vary in the solid stress tensor $\boldsymbol{\sigma}^s$ as described through the momentum equations (3) and (4).

465 For Problems I and II, the first Piola-Kirchhoff stress tensor $\mathbf{P} = \mu^s (\hat{\nabla}^\top \mathbf{d} + \hat{\nabla} \mathbf{d}) + \lambda^s (\hat{\nabla} \cdot \mathbf{d}) \mathbf{I}$ is used in the reference configuration, as seen in (3). To implement the monolithic Eulerian formulation, we convert \mathbf{P} to the Cauchy stress tensor and integrate as follows:

$$\begin{aligned} \int_{\Omega_t^s} \boldsymbol{\sigma}^s : \nabla \delta \mathbf{u} &= \int_{\Omega_t^s} J^{-1} \mathbf{P} \mathbf{F}^\top : \nabla \delta \mathbf{u} \\ &= \mu^s \int_{\Omega_t^s} J^{-1} (\mathbf{F}^\top \nabla^\top \mathbf{d} + \nabla \mathbf{d} \mathbf{F}) \mathbf{F}^\top : \nabla \delta \mathbf{u} + \lambda^s \int_{\Omega_t^s} J^{-1} \text{trace}(\nabla \mathbf{d} \mathbf{F}) \text{trace}(\nabla \delta \mathbf{u} \mathbf{F}), \end{aligned} \quad (\text{A.3})$$

where $\mathbf{F} = \hat{\nabla} \mathbf{d} + \mathbf{I} = \nabla \mathbf{d} \mathbf{F} + \mathbf{I} \Rightarrow \mathbf{F} = (\mathbf{I} - \nabla \mathbf{d})^{-1}$ is computed in the current configuration. 470 As \mathbf{F} depends on the unknown variable, a fixed-point iteration is employed to iteratively compute \mathbf{F} .

For Problem III, the Cauchy stress tensor $\boldsymbol{\sigma}^s = \mu^s (\mathbf{F} \mathbf{F}^\top - \mathbf{I}) - p^s \mathbf{I}$ is used as seen in (4), which can be rewritten as [60]:

$$\boldsymbol{\sigma}^s = \mu^s (\nabla^\top \mathbf{d} + \nabla \mathbf{d} - \nabla^\top \mathbf{d} \nabla \mathbf{d}) - (p^s + \mu^s (\text{trace}(\mathbf{F} \mathbf{F}^\top) - 2)) \mathbf{I}. \quad (\text{A.4})$$

For the numerical implementation of (A.4), we introduce a new variable $q^s = p^s + \mu^s (\text{trace}(\mathbf{F} \mathbf{F}^\top) - 2)$. 475 Equation (A.4) is then expressed in terms of the displacement \mathbf{d} and the new pressure q^s .

Appendix B. Additional test cases

In this appendix, we provide a brief report on the results of some additional, yet special, test cases as supplementary material to the main content of this article. Readers may also 480 refer to additional supporting animations at <https://yongxingwang.github.io/simulation/>.

Appendix B.1. Problem I: compressed plates

Figure B.11 shows the velocity profile, where the fluid velocity remains zero while there is a moving wave in the solid. This result is obtained by modifying the parameter set in Table 1 with $\phi = 3\pi$, in which case nothing happens in the fluid as commented in Remark 4. 485

Appendix B.2. Problem II: compressed discs

A challenging test case can be created simply by setting $R_0 = 1$ in the parameter set outlined in Table 2. As pointed out in Remark 7, a compressed wave propagates in the solid domain, causing the solid mesh to compress and stretch along the radial direction, as shown in Figure B.12. We set $\bar{d} = 0.15$ (5% of the width of the solid domain $R_1 - R_0$) and tested a mesh of 3472 vertices and 7105 triangles, with a time step of 10^{-3} , alongside a remeshing technique to preserve mesh quality. Unfortunately, our simulation breaks down before reaching the maximum displacement at $t = 0.05$. 490

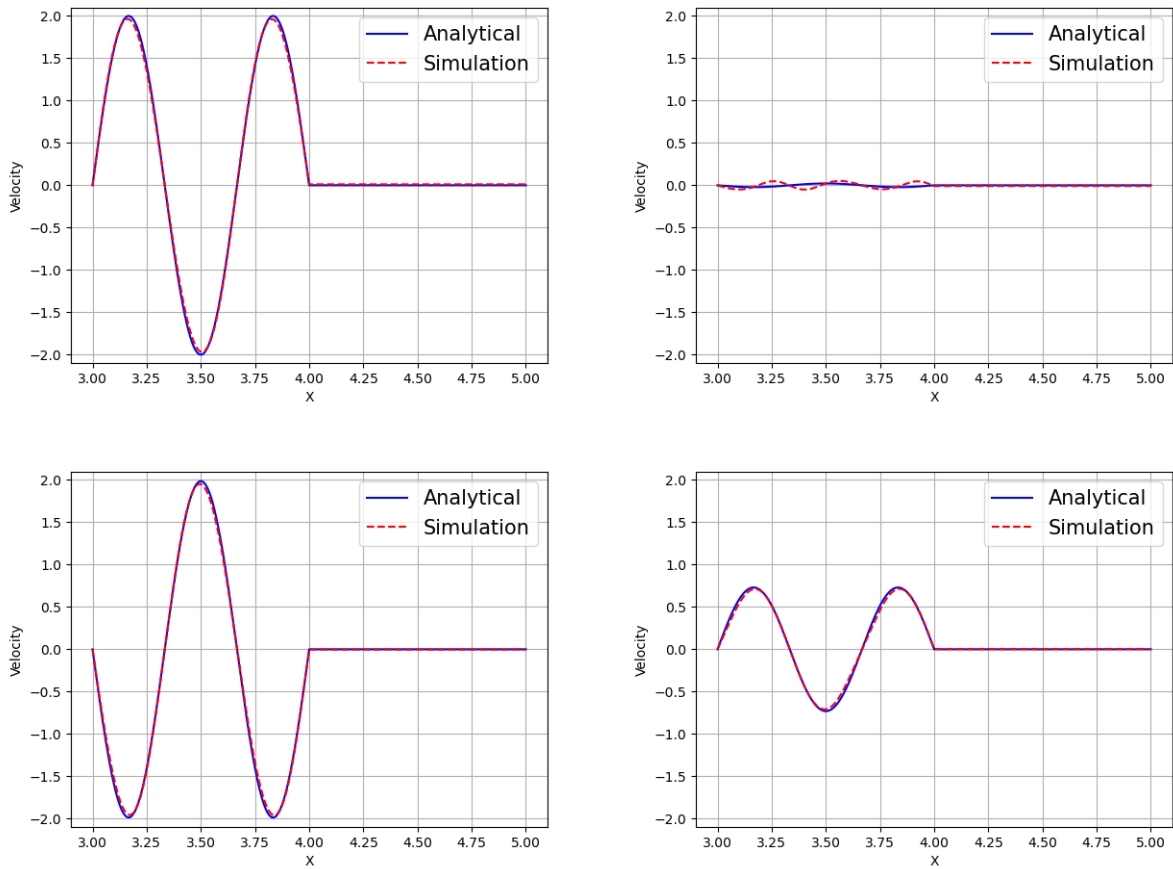


Figure B.11: Velocity profile at different times: $t = 0.43$, $t = 0.425$, $t = 0.475$ and $t = 0.5$ from left to right and top to bottom.

Appendix B.3. Problem III: rotating discs

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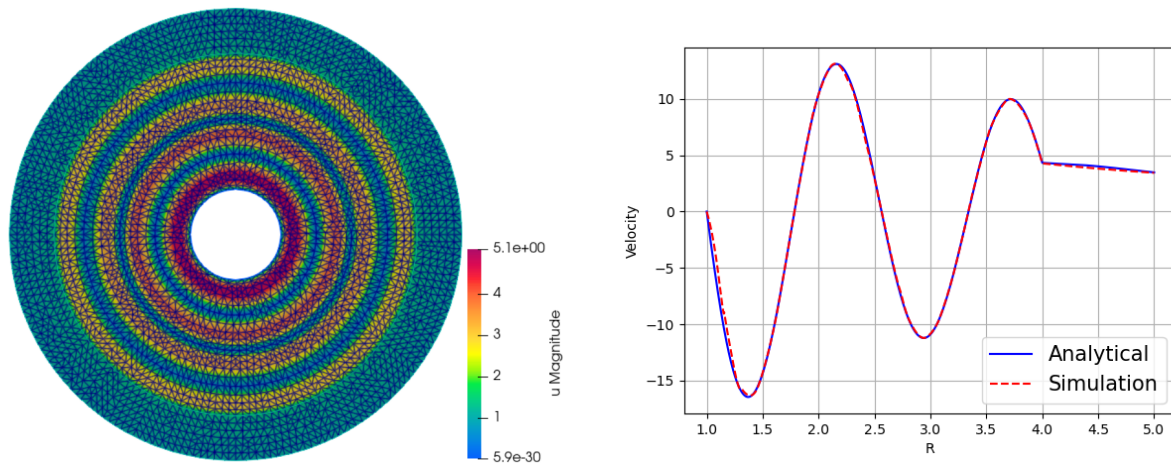


Figure B.12: Velocity magnitude on a 2D mesh (left) and velocity along the radial direction (right) at $t = 0.046$, when $R_0 = 1$ for numerical simulations with multiple compressed waves propagating in the solid. The simulation is run on a mesh of 3472 vertices and 7105 triangles with $\Delta t = 2.5 \times 10^{-4}$.

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