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Abstract

This thesis describes bla bla...

Keywords— one, two, three, four

Sommario

In questa tesi bla bla...

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Chapter 1

Introduction

Fluid-Structure Interaction (FSI) describes the mutual interaction between a moving or deformable object and a fluid in contact with it, surrounding or internal. It is present in various forms both in nature and in man-made systems: a leaf fluttering in the wind, water flowing underground or blood pumping in an artery are typical examples of fluid-structure interaction in nature. FSI occurs in engineered systems when modeling the behavior of turbomachinery, the flight characteristics of an aircraft, or the interaction of a building with the wind, just to name a few examples.

All the aforementioned problems go under the same category of FSI, even if the nature of the interaction between the solid and fluid is different. Specifically, the intensity of the exchanged quantities and the effect in the fluid and solid domains vary among different problems.

There can be multiple ways to classify FSI problems, based on the flow physics and on the behavior of the body. Incompressible flow assumption is always made for liquid-solid interaction, while both compressible and incompressible flow assumptions are made when a gas interacts with a solid, depending on the flow properties and the kind of simulation. The main application of air-solid interaction considers the determination of aerodynamic forces on structures such as aircraft wings, which is often referred to as *aeroelasticity*. Dynamic aeroelasticity is the topic that normally investigates the interaction between aerodynamic, elastic and inertial forces. Aerodynamic *flutter* (i.e. the dynamic instability of an elastic structure in a fluid flow) is one of the severe consequences of aerodynamic forces. It is responsible for destructive effects in structures and a significant example of FSI problem.

The subject may also be classified considering the behavior of the structure interacting with the fluid: a solid can be assumed rigid or deforming because of the fluid forces. Examples where rigid body assumption may be used include internal combustion engines, turbines, ships and offshore platforms. The rigid body–fluid interaction problem is simpler to some extent, nevertheless the dynamics of rigid body motion requires a solution that reflects the fluid forces. Within the deformable body–fluid interaction, the nature of the deforming body may vary from very simple linear elastic models in small strain to highly complex nonlinear deformations of inelastic materials. Examples of deforming body–fluid interaction include aeroelasticity, biomedical applications and poroelasticity.

The interaction between fluid (incompressible or compressible) and solid (rigid or deformable) can be *strong* or *weak*, depending on how much a change in one domain influences the other. An example of weakly coupled problem is aeroelasticity at high Reynolds number, while incompressible flow often leads to strongly coupled problems. This distinction can lead to different solution strategies, as briefly described below.

Physical models aren't the only way in which FSI problems can be classified. The solution procedure employed plays a key role in building models and algorithms to solve this kind of problems. The two main approaches are: the *monolithic approach* in which both fluid and solid are treated as one single system and the *partitioned approach* in which fluid and solid are considered as two separated systems coupled only through an interface. This latter approach is often preferred when building new solution procedures as it allows to use solvers that have been already developed, tested and optimized for a specific domain. The solvers only need to be linked to a third component, which takes care of all the interaction aspects.

The partitioned approach can be further classified considering the coupling between the fluid and solid: the solution may be carried out using a *weakly coupled approach*, in which the two solvers advance without synchronization, or a *strongly coupled approach*, in which the solution for all the physics must be synchronized at every time step. Although the weakly coupled approach is used in some aerodynamic applications, it is seldom used in other areas due to instability issues. A strongly coupled approach is generally preferred, even though this leads to more complex coupling procedures at the interface between fluid and solid.

This work describes the implementation and the validation of what is called an *adapter*, that is the "glue-code" needed to interface a solver to a coupling software library, thus adopting a *partitioned approach* to solve FSI problems. The *adapter* presented here connects the software code *MultiBody Dynamics analysis software (MBDyn)* to the multiphysics coupling library *precise Code Interaction Coupling Environment (preCICE)*.

Interfacing MBDyn with preCICE has multiple advantages: on one side it extends the capabilities of MBDyn to be used in FSI simulations by connecting it with a software library which has been already connected to widely used CFD solvers; on the other side, it allows to describe and simulate FSI problems with a suite of lumped, 1D and 2D elements (i.e. rigid bodies, *beams*, *membranes*, *shells*, etc.) decoupling the shape of the object (the interface with the fluid) from its structural properties, which can be described by different models and constitutive laws.

The thesis is structured as follows:

- Section 2 introduces the reader to FSI problems and their complexity, with particular attention to the physical description of the fluid and solid domains and the interface.
- Section 3 focuses on numerical methods, describing how to computationally deal with these kind of problems: details regarding the different coupling approaches are given here.
- Section 4 explains the features of preCICE that the adapter needs to support and gives a short introduction to MBDyn, explaining the main functionalities of interest.
- Section 5 presents the adapter developed in this work, its most important features and how to configure a FSI simulation with it.
- Section 6 describes the successful validation of the adapter, the comparison of the results with some well-known benchmarks and an example of real world application.
- Section 7 summarizes the the findings and outcome of this work and gives an outlook to future work on this topic.
- Finally XX appendices give further information on...

Chapter 2

Physical aspects of Fluid-Structure Interaction problems

TODO: Intro

2.1 Description of motion

A fluid in motion is considered and interaction with a solid occurs via deformations of the latter due to viscous and/or inviscid forces exerted on the structure by the fluid. The resulting change in shape of the structural material also implicates geometrical changes of the fluid domain. This yields different flow behavior in reverse. Thus, it is necessary to represent kinematic and dynamic processes formally. Therefore, some thoughts concerning the motion of the before mentioned continuum particles must be made. In classical continuum mechanics there are two different perspectives ([26]): The Eulerian description, which is discussed in Section 2.2.1, and the Lagrangian point of view, which I explain in Section 2.2.2. Those two perspectives can be combined to the arbitrary Lagrangean-Eulerian (ALE) method, described in Section 2.2.3.

2.1.1 Eulerian perspective

In a Eulerian perspective the change of quantities of interest (e.g. density, velocity, pressure) is observed at spatially fixed locations. In other words, a Eulerian observer does not vary the point of focus during different time steps. This is depicted intuitively in Figure 2.1. Located at a certain point in Euclidean space, the observer always focuses on the same location, no matter where particles may move. Thus, in Eulerian description, quantities can be expressed as functions of a fixed location as well as time. This may be denoted by:

$$\Theta = \tilde{\Theta}(x, y, z, t) \tag{2.1}$$

where Θ is a quantity of interest and $\tilde{\Theta}$ denotes it in a Eulerian point of view. (x, y, z) represent a fixed position in Euclidean space and t refers to time. Clearly, different particles can occupy the spatial location, which the observer focuses on, at different instances of time. Therefore, in general no direct information regarding the change of quantities of a single particle is available when motion is described in a Eulerian perspective ([26]). Eventually, a description of motion is needed not only for single particles and points in space, but rather computational domains and meshes being central aspects of FSI problems. A computational mesh can be interpreted as a number of observers distributed across the domain of interest and connected so as to form a grid with nodes. If particles of the underlying domain move, a purely Eulerian mesh does not change the positions of its nodes throughout the whole mesh at different instances of time. This is graphically shown in Figure 2.2. Since this behavior of the mesh is independent of large-scale movements of particles, it is the typical choice for CFD problems, where in general fluid particles move throughout the whole computational domain. However, this approach also has its drawbacks as the level of refinement of the mesh is crucial to the accuracy of computations because it defines to what extent small-scale changes can be observed. If a mesh is of a much coarser scale than the motion occurring in the underlying domain, the motion cannot be resolved ([10], [26]).

2.1.2 Lagrangian perspective

A Lagrangian description implies that the observer focuses on a specific particle and follows it, regardless of the speed and distance it may travel. Therefore, provided that the particle moves, changes of the quantities of interest are observed at different spatial locations. The Lagrangian observer tracks a particle and moves with it, as illustrated in Figure 2.3. The motion of the particle as well as all other quantities of interest, can therefore be described by reference coordinates (or material coordinates) in Euclidean space, (X, Y, Z), uniquely identifying the observed particle at a reference configuration. Often $t = 0$ is chosen as reference but in general any time instance can be used. Once the particle to be observed is specified, the Lagrangian observer only registers changes concerning this one particle as time passes. Thus, quantities of interest can be described as

$$\Theta = \hat{\Theta}(X, Y, Z, t) \tag{2.2}$$

Again, computational domains and meshes are considered: At a reference instance of time, usually at the beginning of a simulation, mesh nodes are attached to the underlying material particles. As time passes and particles move, the mesh nodes move with them causing the mesh to deform (except for cases in which all particles move smoothly with equal speed and distance). Figure 2.4 depicts such a situation. As it can be seen, the mesh nodes always coincide with their respective particles. A drawback of this Lagrangian technique is that large-scale and irregular motions lead to distortions of the computational mesh, which yields smaller accuracy in simulations as a consequence of the strictly enforced tracking. However, from this point of view, small-scale motions, which often occur in solids, can easily be observed without the need of using extremely fine meshes, which would be necessary in case a Eulerian perspective was used. This results in reduced computational effort. Therefore, in general, the Lagrangian description is the method of choice for CSM problems ([10], [26]). Eulerian and Lagrangian descriptions are related. A mapping between them can be derived if the motion is known:

$$x_i = X_i + u_i(X_i, t) \quad \forall i = 1, 2, 3 \tag{2.3}$$

Equation 2.4 can be explained as follows: The Eulerian, spatial position x of a particle at time t is the position of this particle at its reference configuration X plus the displacements u that it traveled since the point of time of the reference state ([26]).

2.1.3 ALE method

Finally, I explain the ALE approach, a combination of the Eulerian and Lagrangian perspective widely used for FSI problems. As the name implies, an ALE observer can arbitrarily decide whether to move the point of focus or not. Furthermore, the observer is in no way restricted to the movement of particles. Figure 2.5 depicts such a situation. The observer moves independently of the particle motion. By analogy with the Eulerian and Lagrangian meshes before, an ALE mesh is considered as it can be seen from a Eulerian perspective in Figure 2.6. Mesh nodes can move almost arbitrarily regarding the motion of the underlying particles. The only restriction is, that node movements should not distort the mesh too much as this leads to inaccuracy. It is reasonable to allow the nodes to follow moving particles up to a certain extent, which is defined by mesh quality criteria. Since this approach does not allow to directly link mesh motion and material particle motion, a new unknown is introduced to such a problem, namely the relative movement between the ALE mesh and the material domain. This approach is especially interesting for FSI problems because it is an alternative description to the Eulerian frame for the fluid domain. As it is further explained in Section 2.3.3, fluid and solid material have to follow the moving interface between them for physical reasons. Since the solid domain is usually described in a Lagrangian view, there is no problem with keeping the solid mesh attached to the FSI interface. However, if a purely Eulerian approach was used for the fluid domain, movements of the interface would lead to gaps between the wet surface and the fluid mesh. Therefore, in ALE methods the fluid mesh nodes at the interface always move with it. This can be interpreted as Lagrangian fashion of the approach, as fluid mesh nodes follow the fluid particles sticking to the interface, while the rest of the fluid mesh is allowed to move in such way that mesh distortions are kept minimal in order to preserve computational accuracy. Since preserving mesh regularity refers more to a Eulerian approach, the choice of the name ALE becomes apparent ([32], [10]).

2.2 Domains and interface

As the name fluid-structure interaction implies, this type of problems is determined by the fluid and solid domain, covered in Sections 2.3.1 and 2.3.2, respectively. Furthermore, their interaction is of importance, which underlines the necessity of suitable coupling conditions at the domain common interface. The interface is also referred to as wet surface. Its formal definition is stated in Section 2.3.3

2.2.1 Fluid domain

In the following, all of my considerations are limited to viscous Newtonian flows in the compressible regime as this kind of model is the only relevant one for this thesis. Nevertheless, I want to point out that throughout the FSI community also incompressible and inviscid flow regimes are commonly considered, depending on the type of physical problem. The before mentioned kind of flow is described by the Navier-Stokes equations (NSE), which I consider in the general three-dimensional case in a Eulerian description. They consist of the continuity equation (conservation of mass, Equation 2.5a), the momentum equation (conservation of momentum, Equation 2.5b) and the energy equation (conservation of energy, Equation 2.5c). The equations are shown in index notation. Repeated indices imply Einstein's summation convention. For a detailed explanation of this convention, I refer to [26]. The NSE are usually derived by applying Newton's Law to a fluid control volume and an elaborate derivation can be found in [14]. The equations are taken from [26] and [14].

$$\rho_t + (\rho u_j)_j = 0 \tag{2.4}$$

$$(\rho u_i)_i + (\rho u_i u_j + p\delta_{ij} - \tau_{ij})_j = 0 \quad \forall i,j = 1,2,3 \tag{2.5}$$

$$(\rho e_0)_t + (\rho e_0 u_j + u_j p + q_j - u_i \tau_{ij})_j = 0 \tag{2.6}$$

ρ denotes density, t time, $\mathbf{u}$ flow velocities in all dimensions and p pressure. δ_{ij} is the Kronecker delta, τ the viscous stress tensor, e_0 total energy (per unit mass) and $\mathbf{q}$ heat flux (via conduction). For a Newtonian fluid the viscous stress tensor is given by

$$\tau_{ij} = -\frac{2}{3}\mu u_{k/k}\delta_{ij} + 2\mu S_{ij} \quad \forall i, j = 1, 2, 3 \tag{2.7}$$

With μ being the dynamic viscosity and $\mathbf{S}$ the rate of deformation tensor (symmetric part of the velocity gradient ∇u):

$$S_{i,j} = \frac{1}{2}u_{i/j} + u_{j/i} \quad \forall i, j = 1, 2, 3 \tag{2.8}$$

In order to form a closed set of these partial differential equations (PDE), it is necessary to choose a conductive heat flux model (usually Fourier's Law), specify the caloric and thermodynamic equations of state and finally, choose appropriate initial and boundary conditions for the problem ([17], [14], [26]).

Simplification can be done to obtain easier models such as: adiabatic, inviscid, incompressible...

2.2.2 Solid domain

As described in Section 2.2.2, in solid mechanics usually a Lagrangian point of view is used (as is here), because particles do not travel as far as they do in fluid dynamical problems. Also, the structural model explained in this section is limited to the Saint Venant-Kirchhoff model, which is very common since it is capable of handling large deformations often occurring in FSI problems ([18]). The model assumes that the solid material is homogenous, meaning that mechanical properties of a particle of the body do not depend on the location of the particle. In other words, these properties are the same throughout the whole solid domain. Moreover, isotropy is assumed, such that the direction in which a stress is applied to the solid does not matter, as the mechanical properties of the body are the same in all directions ([26], [45]).

The following explanation is a short version, since this thesis does not focus on the solid mechanical aspects of FSI problems. It is inspired by and partly taken from [18] and [26], where derivations are given to a more detailed level. By analogy with the NSE (see Equations 2.5), the description of the solid arises from considering a control volume and applying Newton's Law to it. A typical equation of motion in the form Mass Acceleration = Forces can be derived (again, the general three-dimensional case is considered):

$$\rho u_{tt} = S_{ij/j} + \rho f_i \quad \forall i, j = 1, 2, 3 \tag{2.9}$$

Here, corresponds to the structure density, the second derivative of the displacements u with respect to time t to the acceleration of a material particle and S to the second Piola-Kirchhoff stress tensor. X denotes the material coordinates as mentioned before. In this case, also the volume force f is considered, because gravity can often not be ignored for solid materials. Again, a constitutive law must be taken into account, defining the relationship between stress and strain:

$$S_{ij} = \lambda E_{kk}\delta_{ij} + 2\mu E_{ij} \quad \forall i, j, k = 1, 2, 3 \tag{2.10}$$

with

$$E_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial X_j} + \partial u_j \partial X_i\right) + \frac{1}{2}\frac{\partial u_k}{\partial X_i}\frac{\partial u_k}{\partial X_j} \forall i, j, k = 1, 2, 3 \tag{2.11}$$

Note that E is the Lagrangian (finite) strain tensor. The latter summand in Equation 2.10 is nonlinear and can be neglected for small deformations, leading to the Lagrangian infinitesimal strain tensor. However, since we deal with possibly large deformations, this relationship remains non-linear. ij again refers to the Kronecker delta. and are material parameters named Lamé constants. They relate directly to Young's modulus E and Poisson ratio , which are of more practical use1. Their relationship is given as follows:

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} \tag{2.12}$$

$$\nu = \frac{\lambda}{2(\lambda + \mu)} \tag{2.13}$$

Either (E; ν) or (λ; μ) are enough to fully characterize this material under specific assumptions:

- The solid is linearly elastic and isotropic.
- The strain tensor E is symmetric,
- as well as the stress tensor S.

Furthermore, a scalar, positive definite strain energy density function (not shown in this shortened explanation) relating stress and strain tensor via a potential formulation exists. For more sophisticated explanations the interested reader may refer to [26].

TODO beam model

2.2.3 Interface and interaction

Since FSI problems are centered on the interaction of the fluid and solid domain, their common interface is of vital importance. A schematic picture of a sample situation at the wet surface is shown in Figure 2.7. Note that all quantities related to the solid and fluid domain, as well as the interface are subscripted with S, F and FS, respectively. Also, in order to avoid simultaneous usage of sub- and superscripts, I switch from index to direct notation in this section. In order to couple both domains via the interface in a physically correct way, some conditions must be met. These conditions are commonly used for FSI problems. However, in this specific case they are taken from [18] and [20]. First of all, fluid and solid domain should neither overlap, nor separate from each other at the interface as there can be no space occupied by fluid and solid particles at the same time and "empty" space is non-physical. Furthermore, for a viscous fluid the flow velocity at the domain boundary has to be equal to the boundary velocity itself, which is called no-slip condition. Together, this results in the kinematical requirement that the displacements of fluid and solid domain, as well as their respective velocities have to be equal at the wet surface (denoted by Γ_{FS}):

$$\vec{x}_F = \vec{u}_S \tag{2.14}$$

$$\vec{v}_F = \frac{\partial \vec{u}_S}{\partial t} \tag{2.15}$$

For inviscid fluids only velocity components normal to the wet surface have to be equal to the structural velocity as the fluid may slip freely in tangential direction at any boundary. It is not sufficient to consider only kinematic constraints at the interface. In addition, an equilibrium of forces at the wet surface is needed such that it is not torn apart by resultant forces. Force vectors originate from the stresses at the interface and the outward normal vectors of fluid and solid domain, respectively. They have to be equal and opposite leading to the dynamic coupling condition:

$$\sigma_F \cdot \hat{n}_F = -\sigma_S \cdot \hat{n}_F \tag{2.16}$$

σ 2 R33 denotes the stress tensor and n 2 R3 the outward normal vector of the fluid and solid domain. Note that here viscous as well as inviscid stresses are included.

2.3 Classification of FSI problems

you have been interested in the effect of boundary conditions on the flow. For instance, here is the effect of a cylinder that deviates a uniform flow. In fluid mechanics, we consider solids as boundary conditions only, and not in terms of what they are made of. In solid mechanics, we usually consider fluids just as the cause of a loading at the boundary, a force type boundary condition. These two approaches are very useful, and I extensively used in engineering. For instance, in civil engineering you may find engineers that compute wind loads on a bridge. And then send them to other engineers that will check that this is acceptable in terms of the solid mechanics of the bridge. This is often quite sufficient. We mean situations where you cannot solve these two problems independently. Here schematically, the cylinder is deformed by the flow, which itself is modified by the deformation of the cylinder. This is coupled fluid and solid mechanics. Now, when you think of it, this question of coupling of models is actually quite fundamental.

First, find a way to classify all these couplings. Why? Because the variety seems so large that it does not seem feasible to find a model that is applicable to all of them. The second objective, once we have classified them is to try and build relevant models for these classes.

So when you want to go from considering dimensional quantities to dimensionless ones, what can you do? There is a rather general theorem called the Pi Theorem or the Vaschy-Buckingham Theorem, which tells you how many dimensionless quantities you need to look for. This theorem states that the number of dimensionless quantities, P, is equal to that of the dimensional ones, N, minus R What is R? It is the rank of the matrix of dimension exponents. This matrix is formed by the columns of the dimension exponents of all variables, as you can see here. Remember that the rank of a matrix is a number of independent lines or columns that you can find. Let us give an example

2.3.1 Dimensional analysis

CFR w1-2

we need to classify all these cases of mechanical coupling between fluids and solids. The tool we shall use is called Dimensional Analysis. It is dimensionless in the sense that we do not need any scale of unit to express it. It is just a number. Here, let us just take as a principle that a physical law should only relate dimensionless quantities. There is a rather general theorem called the Pi Theorem or the Vaschy-Buckingham Theorem, which tells you how many dimensionless quantities you need to look for. This theorem states that the number of dimensionless quantities, P, is equal to that of the dimensional ones, N, minus R. What is R? It is the rank of the matrix of dimension exponents. This matrix is formed by the columns of the dimension exponents of all variables, as you can see here. Let us consider, schematically, the fluid here in blue and a solid in red. To make things simpler, we assume that they stand in separate domain of space and that there is no mass transfer between them. As for the case of drag on a sphere, we now need to specify what quantities we want to use to define our problem and what we are looking for. First, the fluid on the left. Let us say that we're looking for the local velocity U in relation to the coordinate of the point we consider X and the time T. This is also going to depend on the viscosity of the fluid, mu, The density of the fluid rho and the gravity, G. Also the result is going to be different if I change the size of the domain. So I say the result depends on the size L. Of course, this velocity is also going to depend on some boundary condition. For instance, an upstream flow velocity that I call U naught. This is the list of quantities I'm considering in a given problem in the fluid. Second, the solid on the right. We might want to know the displacement, csi, at a position X, at a time T. It may depend on E, the stiffness of the solid, (I shall come back to this later) on it's density, rhoS and on gravity G. Again, it will also depend on the size. And there is somewhere the magnitude of this displacement that is set, say cdi naught. As you can see here, I'm quite general in stating what the problem is. Still by stating that this is the list of quantities that I want to relate by my physical law, I'm not that general. For instance, I've excluded the temperature. But we have to choose what is the kind of problems that we want to consider. And this is already quite general.

2.3.2 Dimensional analisys in fluid domain

CFR w1-3

We are going to start by something very simple. Doing dimensional analysis separately in the fluid and in the solid. Imagine now that what happens in one domain is totally independent of what happens in the other. For instance, in the fluid. This is what you have done in fluid mechanics when you have ignored all possible influence of what happened inside a solid that bounds the fluid. So, we assume that there exist a physical low that relates the fluid velocity with all the other parameters, namely X, T and so on. This means that the flow is not going to depend on the deformation of the solid, because the stiffness E for instance, is not included in there. This is pure fluid mechanics. Let us do the dimensional analysis of this. Here is a law F between the dimensional variables. There are eight. To use pi theorem, I need to build the matrix of dimension exponents. Here it is. X is the coordinate, so it is a length. T is a time. U is a length per time and so on. As soon as you can put some units on these quantities, you can write the dimension exponents. Now, what is a rank of this matrix? We can find three independent vectors. For instance, here. And certainly no more than three because the dimension is three. So the rank is all equal to three. I can conclude that we should be looking for 8 minus 3 equals 5 dimensionless parameters. So, let us write the law we are looking for in the form of one depending on only five dimensionless parameters. What are these dimensionless parameters? We know that we should find five independent ones. I can easily start by defining a dimensional velocity by diving U by U naught. Both are velocities. So the ratio is dimensionless. Second, X divided by L. Third, something I shall explain in a moment. Then, of course, the Reynolds number that combines these four. What else? I haven't used the gravity G so far. So let us use it in a dimensionless number. Here is what is usually called the Froude number combining U naught, G and L. These five members are dimensionless and they are independent. You cannot get one by a combination of the others. Let us go back to the ratio U naught T over L. As all dimensionless quantity, this one can be understood as the ratio of two dimensional quantities, two lengths, two times. I can write this one as T over T fluid where T Fluid equals L over U naught. What is L over U naught? It is just the time taken by a particle of velocity U naught to travel across the distance L. So T fluid is a time scale associated with convection in the fluid. A very important quantity that we shall use later. At this stage, we have just written down the fact that the dimensionless velocity in the fluid is dependent on a dimensionless coordinate, a dimensionless time, the Reynolds number, the Froude number.

2.3.3 Dimensional analysis in solid domain

Let us now do the same for the solid alone. Now, we look for a relation between all quantities on the solid side. F of X,T, csi, E, L, G, tho s chi naught, equals zero. I have singled out the displacement, which is unknown. Let us use again the pi theorem. Here is the matrix of the dimension exponents. We have here, too, 8 quantities, a rank of 3, and so 5 dimensionless parameters to find. What are they? Here is a choice. The dimensionless displacement where I've divided csi by the length L. The dimensionless coordinate or dimensionless time , I will discuss just after, and two other dimensionless parameters. The first one is the ratio between the displacement data csi naught and the length scale of the system. We shall call it the displacement number. When large, the displacements are large with regard to the size. This is what we call usually large displacements. The second one combines gravity, density, length and stiffness and I shall call it the elastogravity number. When it is large, it means that the deformations induced by gravity in the solid are large. For instance, in a jelly cake, the shape is really effected by gravity. Let us go back now to the dimensional time that I introduced. I can write this as T over Tsolid, where Tsolid is L over a velocity C, and this velocity us square root of E over rho s. What is it? It is actually the scale of elastic wave velocities inside the solid. So T solid is the time that an elastic wave takes to go across the solid.

2.3.4 Dimensional analysis of coupled problems

cfr W1-4

We are now ready to undertake the dimensional analysis of a fully coupled fluid and solid interaction problem. We have done the case of the fluid alone and the case of the solid alone We're going to use exactly the same method but considering the fluid and the solid, simultaneously. We are back to our full list of parameters that define the problem. Let us discuss a bit what these quantities are. Some of them are only defined on the fluid side, or on the solid side. This is, for instance, the case of the viscosity mu in the fluid or the stiffness E in the solid. Others are common to both domains such as the gravity g or the scale of lengths L. What about our variables of interest, those that we want to relate to the parameters? I mean, the velocity U or the displacement csi. One of them is defined in the fluid and the other in the solid. But now, we are going to consider that they are related to all the parameters of the problem without separation.

What are these dimensionless quantities in such of problem that mixes fluid and solid ? Let us try to give a set of eight independent dimensionless quantities out of the 11 dimensional ones. I'll start with the one I know. U over U naught, x over L, U naught t over L, the Reynolds number and the Froude number. That makes five. Now, I can also use the ones I know from the solid side, combining the three quantities in a solid, and that gives us the displacement number, csi naught over L, and the elastogravity number, G. That makes 5 + 2 equals 7. But from the pi theorem I know I should use eight dimensionless quantities.

It necessarily mixes things from the fluid and the solid side otherwise I would have found it before when doing the uncoupled case. So what is it? What can we imagine as the dimensionless quantity combining fluid and solid dimensional once.

Mass number

The simplest one is the ratio of the two densities. Let us call it the Mass Number, M. This seems a very good choice because it simply tells you that it is different for a solid to interact with air or with water. In the hard-disk drive example, M is the order of 1, air, over 10 to the 4, metal, and so M is of the order of 10 to the minus 4. Conversely, for the dolphin skin, both media have about the same density, and M is the order of 1.

Reduced velocity

Here is another possible choice, the reduced velocity. It is the ratio between our free velocity, U naught, and the velocity of elastic waves in a solid, c. This also seems a good idea because it contains information on the way the two dynamics are related. It would be quite different between two examples I considered before. The inflatable dam and the dolphin's skin. [MUSIC] As possible new dimensionless parameters I have proposed the ratio of two densities, that was the mass number and the ratio of two velocities, that was the reduced velocity.

Cauchy number

I can also imagine something combining stresses or stiffnes. This here is the Cauchy number. What does it mean? It is the ratio between the fluid loading quantified by the dynamic pressure over a unit square and the stiffness of the solid E. The higher it is, the more the solid is elastically deformed by the flow.

These three are actually the most important ones, and are used a lot. Which one should you choose for your problem? Well as I said before, there is no good choice of dimensionless numbers. But there are efficient choices, that would be more helpful in solving a given problem.

2.4 First Section

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Figure 2.1. First Figure

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Chapter 3

Computational aspects of Fluid-Structure Interaction problems

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Chapter 4

Software Packages used in this work

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Chapter 5

MBDyn Adapter and its integration

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Chapter 6

Validation Test-cases

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Chapter 7

Conclusions

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Appendix A

First Appendix

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Acronyms

FSI	Fluid-Structure Interaction
MBDyn	MultiBody Dynamics analysis software
preCICE	precise Code Interaction Coupling Environment

Bibliography