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Transient large strain contact modelling: A comparison of contact techniques for simultaneous fluid–structure interaction

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HIGHLIGHTS

- A true-transient contact modelling method for FSI simulations is presented.
- Transient FSI contact modelling is necessary to predict fluid dynamics.
- Transient FSI modelling is necessary to predict structural deformation.

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ABSTRACT

Contact between two deformable structures, driven by applied fluid-pressure, is compared for an existing pseudo-transient contact method (the default in the Comsol Multi-physics v3.3 software package) and a new transient method. Application of the new method enables time-dependent and simultaneous Fluid–Structure Interaction (FSI) simulations to be solved. The new method is based on Hertzian contact. It enables truly transient simulations, unlike the default contact method. Both the default and new methods were implemented using a moving Arbitrary-Lagrange–Euler mesh, along with velocity constraints and Lagrange Multipliers to enable simultaneous FSI simulations. The comparison was based on a simple two-dimensional model developed to help understand the opening of a heart valve. The results from the new method were consistent with the steady-state solutions achieved using the default contact method. However, some minor differences in fluid dynamics, structural deformation and contact pressure predicted were obtained. The new contact method developed for FSI simulations enables transient analysis, in contrast to the default contact method that enables steady state solutions only.
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1. Introduction

The aim of this study was to test a new transient two-dimensional contact method in a simultaneous Fluid–Structure Interaction (FSI) simulation. This contact method has been used with Comsol Multi-physics (v3.3, Comsol Ltd, London) to test its application for FSI simulations. The simplifying assumption made was that negligible translation occurred between opposing contacting boundaries. All other contact conditions remained unchanged.

We have previously discussed the limitations of the default contact modelling method using Comsol multi-physics [1,2]; the key limitation is poor transient implementation. Such limitations meant our initial simultaneous FSI simulations of the mitral heart valve only simulated inflow and ignored valve contact [3]. Subsequently the FSI mitral heart valve model was assessed following implementation of the developed transient contact method [4]. However, assessment of its application to simultaneous FSI modelling is currently limited to that mitral heart valve model. A more generic assessment is necessary to enable its application more widely. There are potential applications to other recently developed FSI heart valve models [5] and to articular cartilage, found at the end of bones in joints such as the hip and knee, where load bearing and hydration are important to its mechanics [6]. For example, there is evidence that replacement materials for articular cartilage which mimic its physical behaviour are advantageous [7], with biphasic models often used to study how cartilage on cartilage contact induces flow of the underlying fluid [8]. Beyond the biomedical field, micro-electro-mechanical-systems often use cantilevers which are deformed through fluid flow [9], leading to potential applications in models with which to study their application for say nanotribology [10]. Hence, a generic description enables the study of FSI which involves contact modelling to be extended beyond the assumption of a rigid contacting surface [11].

In this paper, our new contact method is compared with the existing (default) contact method under FSI conditions, where

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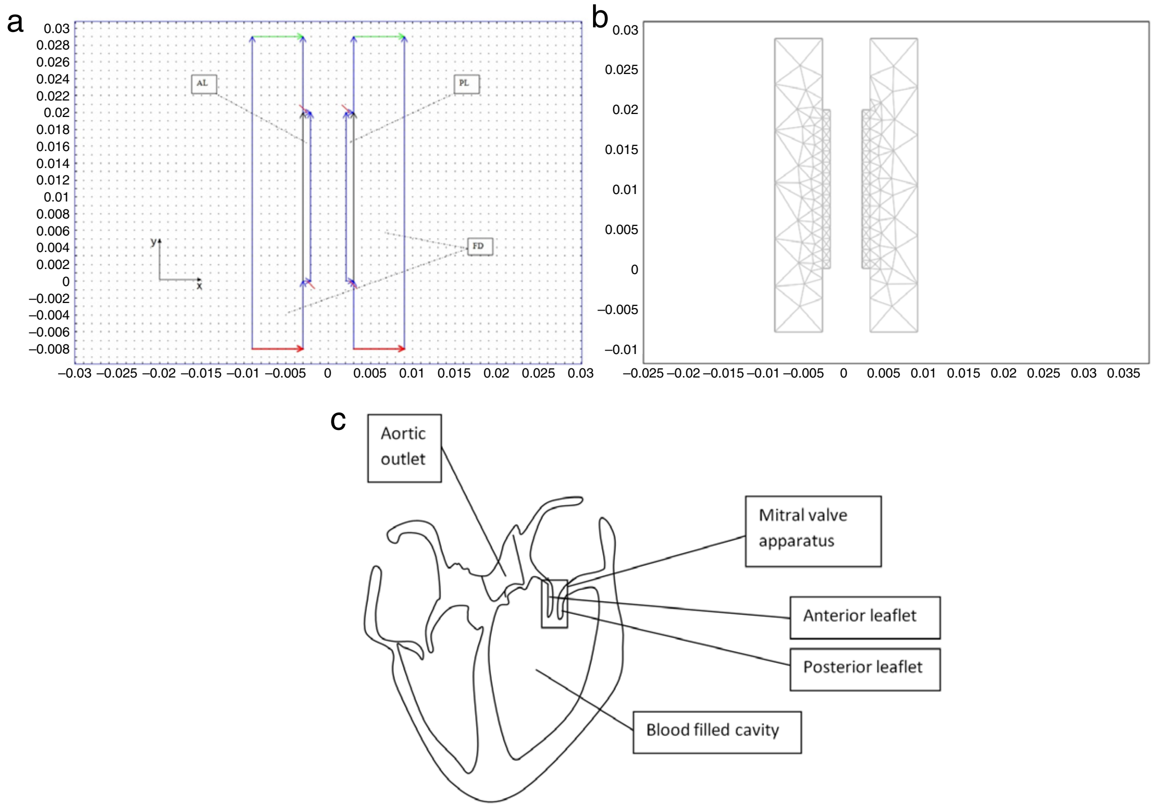

Fig. 1. Geometry, boundary conditions and mesh for simulations. (a) On the larger rectangles (i.e. conduits): red boundaries denote the application of pressure, green boundaries the fluid velocity, and blue boundaries a no-slip condition; on the smaller rectangle (deformable structure, i.e. leaflets): the shorter blue sides with a red line denote a fixed boundary, while the blue boundary denotes the application of contact conditions; FSI occurs through the shared black boundary (i.e. use of velocity constraints and Lagrange multipliers). (b) Mesh used for FSI simulations. Scales are in metres. The deformable rectangle to the left is referred to as the anterior, and to the right the posterior, leaflet. Note, the solid domain is formed by AL (anterior leaflet) and PL (posterior leaflet); while the fluid domain (FD) is contained within the conduits (i.e. larger rectangles within which fluid flow will occur). (c) Illustration of the heart, focusing on the left side of the heart which contains the mitral valve, surrounded by blood. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hydrodynamic fluid flow induces contact by inducing large strain in the structure. Solutions for fluid and structure response were calculated simultaneously for each time step, i.e. ‘true’ multi-physics simulations were performed, as opposed to one-way or iterative coupling of physical states [12]. The Comsol Multi-physics package was used for this study as it allows simultaneous coupling of distinct physical states, as in FSI. Therefore, it is not necessary to iterate between Finite Element (FE) and Computational Fluid Dynamics (CFD) simulation software.

Simultaneous FSI simulations use Lagrange multipliers for non-ideal weak-form constraints, equivalent to the reaction forces on boundaries shared by a structure and fluid [13–15]. During FE analysis Lagrange multipliers enforce constraints; for simultaneous FSI simulations the Lagrange multipliers are also used to determine reaction forces [13–15]. The velocity of the moving structure provides a boundary condition for the fluid velocity at the boundary between the structure and fluid [13–15]. The mesh used for calculating fluid hydrodynamics is typically fixed to the original geometry (using an Eulerian method), but the mesh to determine structural deformation usually follows the deforming shape of the structure (it uses a Lagrangian method). In order to couple the two meshes, an Arbitrary-Lagrange–Euler (ALE) mesh is used [16,17]. A standard ALE mesh is not recommended for large strain modelling; hence, a moving ALE mesh approach has been used which removes the need for computationally expensive remeshing [18].

This new transient contact method is based on Hertzian contact. It has been developed for two-dimensional large-strain conditions, roughly replicating those relevant to heart valve closure. Therefore, structure and fluid properties used in this study resemble those of heart valves and blood. However, this contact method is generic and, thus, applicable to other FSI simulations where contact modelling is important.

2. Methods

2.1. Overview

A new transient FSI contact method and the default contact method available in the software [19] were compared. Contact simulations were simultaneous, transient multi-physics models, with the force that induces contact being applied by fluid flow and pressure. The default contact method solves steady-state solutions for the conditions at the stated time-step.

2.2. Geometry

Two identical conduits were set beside one another with two deformable structures (termed anterior and posterior valve leaflets, because of the intended application to heart valves) attached to their larger facing side (Fig. 1). The two leaflets were the only deformable structures; thus, only leaflets could come into contact. The leaflet geometry used is identical to that used for a static FE analysis described previously [1]. These leaflets correspond, roughly, to the two contacting leaflets of the mitral valve of the heart (a valve that closes due to contact between the two leaflets). The conduits in which fluid flows do not resemble the heart, but they do allow fluid flow to induce leaflet deformation,

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