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Research paper

Computationally efficient approach for simulation of multibody and hydraulic dynamics

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ABSTRACT

A realistic real-time simulation of a complex system, such as an excavator, requires detailed description of the machinery and its components. To take into account the dynamics of entire systems, the model must encompass descriptions of non-mechanical systems, such as hydraulics. For the multibody systems, use of the semi-recursive methods has often been found to be the most efficient solution when the system size increases. For the hydraulic dynamics, in turn, the recently introduced application of the singular perturbation method is a potential candidate for the real-time applications. The main benefit of the application of the singular perturbation method over the conventionally used lumped fluid method is that it overcomes the challenges that the lumped fluid method encounters when numerical stiffness caused by small hydraulic volumes is present in the circuit. Objective of this paper is to improve a recently proposed monolithic formulation for the combined simulation of multibody and hydraulic dynamics via the introduction of the singular perturbation method. Results indicate that the proposed method improves efficiency and robustness when compared to the formulation proposed earlier.

1. Introduction

The use of the multibody-based real-time simulation tools has become more widespread as computation power has grown more affordable. Applications of this real-time simulation are found, for instance, in user training and, recently, in product development [1]. Since real-world mechanical systems are often accompanied by other dynamic systems, such as hydraulics, descriptions of the both dynamic systems are required if an accurate model is to be built.

Several approaches have been proposed to couple the descriptions of the dynamic subsystems, such as co-simulation [2,3] and co-integration [4,5], both of which allow different time steps to be used for each subsystem. These methods are often used to address the significantly different time scale that certain systems, such as multibody and hydraulic dynamics, possess, or, more commonly, to allow the use of the domain-specific tools and solvers developed for each field. This increases modularity in the design process and adds a possibility to hide the internal details of subsystems, for intellectual property protection, but it increases the complexity of the coupling interface.

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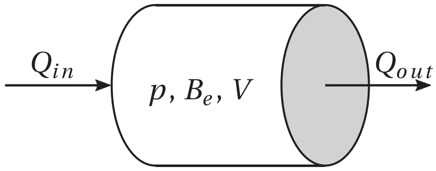

Fig. 1. Idealisation of a volume in the lumped fluid method.

However, if equations for each subsystem are available in the same simulation environment, as seen in [6], use of a monolithic approach, which yields a single set of nonlinear equations to be solved, can provide a straightforward approach for the coupling. This approach has been presented multiple times in the literature, for instance, in [7,8]. In the latter work, the augmented Lagrangian method based on position level constraints and projections [9,10] for constraint stability is coupled with the lumped fluid [11] method and integrated with the implicit single-step trapezoidal rule. As the penalty scheme with iterated Lagrange multipliers and implicit integrator can provide a robust approach for multibody dynamics [10], the work presented in [8] seems interesting from the coupled simulation point of view.

The efficiency of the method proposed in [8] is, however, hindered by the global approach used for the multibody dynamics. To address this, Rahikainen et al. [12] proposed to use the semi-recursive formulation proposed by Cuadrado et al. in [13] for the monolithic simulation of multibody and hydraulic dynamics, based on work presented in [8]. The multibody method uses the same penalty formulation as the augmented Lagrangian method for closed loop constraints and uses the mass-damping-stiffness orthogonal projections [10] to stabilise them, and it has indicated potential for real-time simulation in multiple applications, as demonstrated in studies of automated differentiation tools [14] and dense, sparse, and parallelisation techniques [15].

However, while the multibody method was selected real-time simulation in mind in [12], the lumped fluid method [11] may in certain cases encounter problems, that hinder its computational efficiency. As demonstrated in the literature [16,17], small volumes in a hydraulic circuit can increase numerical stiffness of the system, and thereby require small time steps for a solution to be sought. This can become an issue especially in the context of the monolithic approach wherein the same time step is also used for the multibody solution.

Recently, Kiani et al. [18] proposed application of the singular perturbation theory [19] to address the issue of numerical stiffness introduced by the small volumes. The results of the study indicated potential for the real-time simulation of a hydraulic system, as the behaviour of the examined circuit examined was captured with high accuracy while the computational effort was lower than in the lumped fluid approach. Use of the perturbation method allows to increase the integration time step, which, in turn, decreases the time scale difference between the multibody and hydraulic dynamics.

The objective of this paper is to improve the real-time applicability of the method presented in [12] by employing the approach based on the singular perturbation theory presented in [18]. Accordingly, this is the first study to couple the application of the singular perturbation theory [18] with the multibody dynamics. A case example seen in [12] is modified such that the issue of small volumes with the lumped fluid method is demonstrated, and real-time applicability is evaluated relative to the method presented in [12].

The rest of this paper is structured as follows: Section 2 includes the hydraulic modelling with use of the lumped fluid method and provides a brief introduction to the singular perturbation theory, multibody modelling, and the integration scheme. To better illustrate the application of the singular perturbation theory, Section 3 details the differences in the hydraulic modelling with respect to the lumped fluid method. That section also details the hydraulic circuit and the mechanical model used in the example. Results are presented in Section 4, and Section 5 presents the key conclusions.

2. Methods

In this section the lumped fluid method, which is traditionally used to model the hydraulic circuits, along with the singular perturbation theory, the method applied for the hydraulic circuit here, are briefly introduced. Models of hydraulic components related to the case example, and the implementation details of the singular perturbation theory can be found further on, in Section 3. The semi-recursive multibody method and the monolithic integration also are briefly discussed in this section.

2.1. The lumped fluid method

In the lumped fluid method [11] the hydraulic circuit is divided into volumes V in which pressure is assumed to be equally distributed. This is illustrated in Fig. 1, where volume flows Q_{in} and Q_{out}, both of which may consist of multiple separate flows, flow into volume V, which has internally constant pressure p and effective bulk modulus B_e.