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Substructuring and model reduction of pipe components interacting with acoustic fluids

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Abstract

This paper presents a model reduction and substructure technique for reduced dynamical models of fluid-filled pipe components. Both linear acoustical domain and structural domain are modelled by finite elements (FE), and they are fully coupled by a fluid–structure interface. The discretised dynamic FE-equations, which use the acoustic pressure as field variable in the fluid, render both non-symmetric mass and stiffness matrices due to the FSI-coupling. Since the partial solutions to the eigenproblem of the coupled system are of special interest, either numerical preconditioning or non-dimensionalisation of the physical quantities is performed to improve the condition and to accelerate the numerical computation. An iterative subspace solver is adopted to generate a sufficient approximate of the low-frequency eigenspace of the constrained problem. Model reduction for component mode synthesis uses constraint modes together with the computed eigenspace. Single-point constraints for the nodal degrees of freedom hold at the interface between substructures. The null space resulting from a QR-decomposition of the single-point constraints at the interface is used as explicit coupling matrix to prevent the deterioration of the conditioning. Partitioning of the reduction space and coupling matrices leads to a structure of the coupled global system matrices, which is similar to the original system structure in physical quantities. Therefore, the iterative subspace eigensolver is used again for numerical modal analysis. Modal analysis is performed for a pipe segment assembled by fully coupled two-field substructures. The results are compared to the results obtained from the full model and to experimentally determined mode shapes.

Keywords: Flexible piping system; Acoustic fluid–structure interaction; Reduced component model; Substructuring

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1. Introduction

Vibrations and acoustics of structural components with enclosed fluids are investigated for engineering applications such as flexible piping systems in chemical engineering, pipelines for the transport of fluids, water tanks as well as hoses and pipe components as part of high-pressure hydraulic systems just to name some. Special interest of the investigations is placed on the structural behaviour with respect to the functionality and to structural damage as a result of undesired responses to system excitation. Moreover, the acoustical path is of major interest in the field of noise reduction. It was found early, that both the acoustical fluid and the structural domain interact. As a result of this interaction, the sound speed in a fluid decreases in the presence of a flexible pipe [1], whereas structural waves and modes are affected as well by the properties of the fluid. In order to overcome the restriction to plane waves, fully coupled two-field models in three dimensions guarantee reliable modal and transient analysis. These models are either derived analytically [2] or they exist as a discretised model [3,4] either by the finite element (FE) method or by the boundary element method [5,6]. Thus, it is possible to simulate bending deformations in piping systems, which are responsible for structural failure predominantly. The influence of the fluid–structure interaction is also reflected by modal parameters. For example, longitudinal Helmholtz modal frequencies decrease if the fluid interacts with an elastic pipe wall as compared to the same mode in a rigid duct, whereas the presence of a fluid in the pipe lowers bending frequencies mainly due to the additional inertia of the water [7].

Piping systems are often built up by recurrent standard components, as for example pipe segments, joints and flanges. These components are furthermore assembled in different combinations to complex piping systems. A proper analysis of the acoustical and dynamical behaviour of sufficiently discretised piping systems in three dimensions is, however, challenged by the large number of degrees of freedom (dofs). This motivates the use of substructures (super elements) representing the dynamics of the components of the overall piping system. An automated multi-level-substructure technique (AMLS) [8,9] for interior acoustic problems uses domain decomposition and substructuring techniques for efficient numerical acoustic analysis. The presented method uses similar steps and adopts necessary changes to meet the special conditions and needs in pipe engineering. A typical feature of piping systems is the narrow shape of the pipe elements with relatively small interfaces between each other. Indeed, these coupling interfaces are of major interest since all propagating waves pass them. Therefore, a proper model reduction of the substructure with respect to the coupling interface leads to a significant reduction of the number of dofs, while sufficient information about the dynamic behaviour of the system is retained. The interfaces contain both a fluid and a structural partition as depicted in Fig. 1, such that existing component mode synthesis (CMS) techniques [10], known for structural components are adopted for the coupling of the substructures. A FE model is favoured because the investigated pipes represent an interior acoustic problem with a rather limited number of dofs in the fluid partition. Besides, it is possible to perform modal as well as transient analysis by means of the same mathematical model. Eigensolutions for the non-symmetric FSI-coupled system are needed to generate reduction bases for super elements and to solve the overall system. Hereby, one is usually interested in the partial solution in the low-frequency spectrum. The numerical solution turns out to be a challenge due to the non-symmetric coupling terms and due to poor numerical conditioning, if the model is generated by using SI-units. The latter problem can be overcome