Acoustic Fluid-Structure Interaction of Cars and Ships

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1 Introduction

This lecture explains various phenomena of acoustic fluid-structure interaction and shows how to efficiently model the two-field problem. In general, heavy fluids such as water, oil, fuel or brake fluid influence the structural field and vice versa. More- over, strong coupling is observed if acoustic fluids interact with thin or slender structures. Important fluid-structure interaction phenomena in practical applications are

- shift of natural frequencies,
- change of wave number and fluid wave speed,
- pressure-induced vibrations,
- sound radiation.

The above mentioned phenomena are present in automotive and ship applications such as fluid-filled brake/fuel pipes, exhaust systems or partly immersed ship hulls. The considered applications are characterized by a negligible mean flow (Mach number << 1), which allows the use of the linear wave equation for a fluid at rest to describe the acoustic field. To predict the hydro- and vibro-acoustic behavior of these industrial examples, three-dimensional models including full coupling of the two-field problem are needed. Appropriate coupling conditions are

- the linear Euler equation enforcing continuity of particle velocities in the normal direction at the fluid-structure interface,
- the reaction force axiom enforcing equilibrium.

In the presence of a heavy fluid, the natural frequencies of longitudinal and flexural wave types in the structure are shifted due to the added mass or the added stiffness effect (shift to lower or higher frequencies, respectively). The torsional wave is not influenced by the acoustic field since no deflection in the normal direction at the fluid-structure interface occurs.

Pressure-induced vibrations are a common problem in automotive piping systems, where oscillating pressure pulsations excite the flexible pipe shell due to fluid-structure coupling. To predict the resulting vibration levels, adequate damping models are needed. The use of a complex wave number is required to model fluid damping. In thin fluid-filled pipes, friction effects close to the pipe wall are the dominant damping mechanism.

In general, two types of structure-acoustic problems can be distinguished. The interior acoustic problem is characterized by an acoustic fluid which is surround by a flexible structure. A typical exterior acoustic problem is the sound radiation of vibrating structures in the exterior acoustic field. It is particularly important to account for flexural vibrations, which are predominantly responsible for noise and vibration harshness (NVH). Simulation methods for both problems are briefly described in the following.

2 Interior Acoustic Problem

The finite element method (FEM) is considered as the appropriate discretization method to investigate the dynamics of the interior vibro-acoustic problem since only a finite volume has to be discretized. However, large-scale examples require model reduction techniques to accelerate the computation times. The application of the Craig-Bampton method to the vibro-acoustic problem including an additional reduction of the remaining interface degrees of freedom leads to a considerable model reduction. Dynamic substructuring techniques are particularly efficient for systems with repeating substructures, since the corresponding component system matrices and the reduction basis has to be computed only once. The simulation technique is applied to fluid-filled automotive piping systems. Computed transfer functions are validated by a hydraulic test bench operating in the kHz-range.

It is observed, that for structures with a high impedance mismatch between the structure and the contained fluid, the coupled natural frequencies and eigenvectors are altered only marginally compared to the uncoupled ones. Therefore, in such a case, the reduced-order model is constructed by using the uncoupled eigenvectors, since they span approximately the same subspace as the coupled eigenvectors. This is equivalent to reducing each domain separately. However, the reduced-order model is still a fully coupled system. This approach has the advantage that for each domain the favorable reduction method may be applied. For instance, the Rubin method may be used for the reduction of the structural partition and the Craig-Bampton method may be applied to reduce the fluid partition. This combined approach is applied to a rear muffler with an air-borne excitation.

3 Exterior Acoustic Problem

The boundary element method (BEM) is well-suited for the solution of exterior acoustic problems since the Sommerfeld radiation condition is intrinsically fulfilled. Another advantage of the BEM is that only the boundary of the structure has to be discretized, which reduces the effort of mesh generation. To overcome the drawback of high memory consumption due to fully populated system matrices, fast BE methods are used, such as the fast multilevel multipole BEM as well as the concept of hierarchical matrices. FE-BE coupling schemes are developed for ship applications, where the ship hull is influenced by the surrounding water and vice versa. Due to

the large fluid-structure interface, the reduction of interface degrees of freedom is an important step to obtain moderate computation times.

Fast BE methods are also used to compute the sound radiation of automotive structures such as a rear muffler of an exhaust system. Here, both an interior and an exterior acoustic problem have to be solved. The feedback of the exterior acoustic pressure on the vibrating structure may be neglected as long as the impedance mismatch between the two fields is large enough (e.g. stiffened structures surrounded by air).

4 Content of Lecture and Selected Publications

The lecture consists of the following parts:

1. Introduction/Motivation
2. Acoustic Fluid-Structure Coupling
3. Finite Element Method
4. Dynamic Substructuring of the Two-Field Problem
5. Fast Boundary Element Method for the Exterior Acoustic Problem
6. Automotive Applications along with Experimental Techniques
7. Ship Applications
8. Conclusion

The topics of the lecture are taken from articles and archival publications of the author and his co-workers focused on fluid-structure interaction problems. Selected recent publications including abstracts are listed in the following.

1. M. Fischer and L. Gaul: Fast BEM-FEM mortar coupling for acoustic-structure interaction

   International Journal for Numerical Methods in Engineering 62: 1677-1690, 2005

   A coupling algorithm based on Lagrange multipliers is proposed for the simulation of structure-acoustic field interaction. Finite plate elements are coupled to a Galerkin boundary element formulation of the acoustic domain. The interface pressure is interpolated as a Lagrange multiplier, thus, allowing the coupling of non-matching grids. The resulting saddle-point problem is solved by an approximate Uzawa-type scheme in which the matrix-vector products of the boundary element operators are evaluated efficiently by the fast multipole boundary element method. The algorithm is demonstrated on the example of a cavity-backed elastic panel.

2. L. Gaul and M. Fischer: Large-scale simulations of acoustic-structure interaction using the fast multipole BEM

ZAMM 86: 4-17, 2006

For the simulation of acoustic-structure interaction problems, the coupled field equations must be solved. The structure is commonly discretized using finite elements, whereas for the acoustic field the boundary element method (BEM) is favorable. A mortar BEM-FEM coupling algorithm is developed that allows the combination of non-conforming meshes. The high flexibility for the choice of discretizations offers a high efficiency, since specialized shape functions and adaptive mesh refinement can be used in the subdomains. The mortar coupling algorithm yields a saddle point problem that is solved using a preconditioned in- exact Uzawa algorithm. The iterative solver enables the use of the fast multipole BEM and thus coupled simulations on large boundary element models.

3. M. Maess and L. Gaul: Substructuring and model reduction of pipe components interacting with acoustic fluids

Mechanical Systems and Signal Processing 20: 45-64, 2006

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 fluidstructure 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 FSIcoupling. 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.

4. M. Maess , J. Herrmann and L. Gaul: Finite element analysis of guided waves in fluid-filled corrugated pipes

Journal of the Acoustical Society of America 121: 1313-1323, 2007

Free wave propagation in fluid-filled corrugated pipes is analyzed using finite element methods in combination with a wave-based approach. By combining discretized models with a wave-based approach, complex mechanism of wave motion in the three-dimensional waveguide is fully included. The pipes are treated as waveguides having periodic properties in the direction of wave propagation.

The analysis of these guided waves leads to dispersion curves which show the strong frequency-dependency of the different wave modes. The method also al- lows the inclusion of coupling between fluid-borne and structure-borne wave modes which occur at the acoustic-structure interface. Phase and group velocities of the wave modes are derived in postprocessing steps. Additionally, the energy ratio of the fluid-domain and solid-domain vibrational energies is computed. Finally, linear damping models are included in order to explore wave mode attenuation.

5. D. Brunner, M. Junge and L. Gaul: A comparison of FE-BE coupling schemes for large scale problems with fluid-structure interaction

International Journal of Numerical Methods in Engineering 77: 664-688, 2008 To predict the sound radiation of structures, both a structural problem and an acoustic problem have to be solved. In case of thin structures and dense fluids, a strong coupling scheme between the two problems is essential, since the feed- back of the acoustic pressure onto the structure is not negligible. In this paper, the structural part is modeled with the finite element (FE) method. An interface to a commercial FE package is set up to import the structural matrices. The exterior acoustic problem is efficiently modeled with the Galerkin boundary element (BE) method. To overcome the well-known drawback of fully populated system matrices, the fast multipole method is applied. Different coupling formulations are investigated. They are either based on the Burton-Miller approach or use a mortar coupling scheme. For all cases, iterative solvers with different preconditioners are used. The efficiency with respect to their memory consumption and computation time is compared for a simple model problem. At the end of the paper, a more complex structure is simulated.

6. M. Junge, D. Brunner, J. Becker and L. Gaul: Interface reduction for the Craig- Bampton and Rubin Method applied to FE-BE coupling with a large fluid- structure interface

International Journal of Numerical Methods in Engineering 77: 1731-1752, 2009

Component mode-based model-order reduction (MOR) methods like the Craig- Bampton method or the Rubin method are known to be limited to structures with small coupling interfaces. This paper investigates two interface-reduction methods for application of MOR to systems with large coupling interfaces: for the Craig-Bampton method a direct reduction method based on strain energy considerations is investigated. Additionally, for the Rubin method an iterative reduction scheme is proposed, which incrementally constructs the reduction basis. Hereby, attachment modes are tested if they sufficiently enlarge the spanned subspace of the current reduction basis. If so, the m-orthogonal part is used to augment the basis. The methods are applied to FE-BE coupled systems in order to predict the vibro-acoustic behavior of structures, which are partly immersed in water. Hereby, a strong coupling scheme is employed, since for dense fluids the feed- back of the acoustic pressure onto the structure is not negligible. For two example structures, the efficiency of the reduction methods with respect to numerical effort, memory consumption and computation time is compared with the exact full-order solution.

7. J. Herrmann, M. Maess and L. Gaul: Substructuring including interface reduction for the efficient vibro-acoustic simulation of fluid-filled piping systems *Mechanical Systems and Signal Processing* 24: 153-163, 2010

The operation of pumps and valves leads to strong acoustic excitation in fluid- filled piping systems. Efficient substructuring and model order reduction strategies are required for the sound prediction in piping systems, and in order to reduce the sound transmission to attached components, such as the floor panel in vehicles, for example. This research presents a finite element based automatic substructuring and component mode synthesis technique, which is a combination of an extended Craig-Bampton method for fluid-structure coupled piping systems and a novel, consecutive interface reduction. Hereby, the remaining interface degrees of freedom between different substructures are further reduced using appropriate Ritz vectors. The proposed model order reduction strategy accelerates the computation of transfer functions in fluid-filled extended piping systems. In order to validate the simulation results, experimental results are obtained by a hydraulic test bench for dynamic measurements, where fluid pulsation is induced by piezo-driven transducers. The observed fluid-structure interaction phenomena correspond to the predictions by the proposed computation approach.

8. J. Herrmann, J. Koreck, M. Maess, L. Gaul and O. von Estorff: Frequency- dependent damping model for the hydroacoustic finite element analysis of fluid- filled pipes with diameter changes

Mechanical Systems and Signal Processing 25: 981-990, 2011

The integration of a model for longitudinal hydroacoustic fluid damping in thin hydraulic pipes in 3D finite element models is presented in this paper. In order to perform quantitative prediction of the vibroacoustic behavior and resulting noise levels of such fluid-structure coupled system due to hydraulic excitation, an accurate frequency-dependent fluid damping model including friction effects near the pipe wall is required. This step is achieved by matching complex wave numbers from analytical derivation into a parameterized damped wave equation and consecutive translation into finite element modeling. Since the friction effect close to the pipe wall changes locally with the inner pipe radius, the fluid damping model is applied segment-wise in order to model the influence of cross-sectional discontinuity, such as orifices, on the oscillating pressure pulsations. A component synthesis approach, which uses pipe segments as substructures, allows a simple model generation and fast computation times. The numerical harmonic results are compared to experimental frequency response functions, which are performed on a hydraulic test bench driven by a dynamic pressure source in the kHz-range.