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Space-mapping in fluid–structure interaction problems

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Abstract

Transient response due to gust loads can lead to structural failure despite the fact that the aero-elastic system is asymptotically stable. Unsteady aeroelastic analysis should therefore be included in the load calculation cycle of the aircraft design process. Especially in the transonic regime, partitioned strong coupling algorithms perform better than loose coupling algorithms and allow larger time-steps in the unsteady simulation. However, the simulation of high fidelity unsteady fluid–structure interaction using strong coupling algorithms is currently too expensive in order to be useful in industry.

To accelerate high fidelity partitioned fluid–structure interaction simulations we apply space-mapping, which is a technique that originates from the field of multi-fidelity optimization. Without loss of generality we assume the availability of a cheap low fidelity fluid solver and an expensive high fidelity fluid solver. The space-mapping approach is used to accelerate the high fidelity computation using black-box input/output information of both the high fidelity fluid solver and low fidelity fluid solver. In order to achieve this, a space-mapping function is defined on the fluid–structure interface which keeps track of the differences between the high fidelity model and the low fidelity model during the coupling iterations. Reformulating the root-finding problem on the fluid–structure interaction interface using the space-mapping function results in the Aggressive Space-Mapping algorithm.

The Aggressive Space-Mapping algorithm is applied to 1-D and 2-D test cases in order to assess the speedup with respect to the Quasi-Newton Inverse Least Squares algorithm. The latter is considered to be the current state of the art in partitioned strong coupling algorithms. The observed speedup depends mainly on the type of FSI problem and the time step size. The maximum observed speedup is about 1.5.

The application of the space-mapping technique to partitioned fluid–structure interaction problems is found to be a promising approach. The framework is non-intrusive and allows the reuse of existing solvers which is especially useful in an industrial environment. It is expected that the space-mapping technique can be combined with higher order time integration schemes that maintain accuracy over a large range of time step sizes.

Keywords: Fluid–structure interaction; Strong coupling; Space-mapping; Multi-fidelity; Non-intrusive; Black-box

1. Introduction

Fluid–Structure Interactions (FSI) play a central role in aerospace engineering and many other fields like civil, mechanical and biomedical engineering [1,2]. Unstable interactions like wing flutter and buffeting can cause structural failure and prediction of their occurrence is of primary importance in the design of aircraft [3]. Asymptotic stability is

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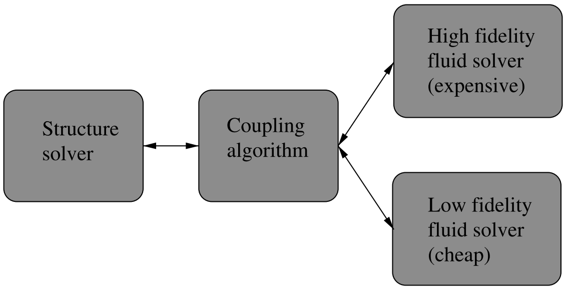

Fig. 1. Schematic of a multi-fidelity coupling algorithm.

a necessary but insufficient condition to guarantee structural integrity. It has been shown that transient growth, induced by sources of external excitation such as gust loads, can lead to structural failure despite the fact that the system is asymptotically stable [4,5]. Unsteady aeroelastic analysis can overcome the shortcomings of asymptotic analysis but it is computationally much more expensive. As an example, the analysis of 50 flight points in the flight envelope for 100 mass cases, 10 control surface configurations, 50 manoeuvres, and 4 control laws would already result in 10,000,000 unsteady aeroelastic simulations to perform a single load calculation cycle. Using engineering experience and lower fidelity models, often corrected with costly wind tunnel data, the current load calculation cycle requires more than 6 weeks, [6].

The replacement of low fidelity simulations with more accurate aeroelastic simulations is attractive because it reduces the number of design cycles, the development risk, the number of flight tests, the cost and time to market and the risk of design modifications in the later design phases [7]. However, the computational effort associated with high fidelity aeroelastic models currently precludes their direct use in industry. Acceleration of time-accurate high fidelity aeroelastic simulation algorithms has therefore become an active area of research, using e.g. multi-level approaches [8–11], multi-solver approaches [12], Interface-GMRES(R) [13,14], Aitken's method and vector extrapolation [15,16] and the Quasi-Newton Inverse Least Squares (QN-ILS) method [12,17–19].

The QN-ILS method has become a popular method due to its combination of efficiency and simplicity, see [12,17,19] and its thorough theoretical basis, see [18]. In [19] it was found that the QN-ILS method outperforms Aitken's method and the Newton–Krylov method from [13] when applied to a (nonlinear) strongly coupled FSI problem. In [18] it was found that the QN-LS method is only slightly slower than GMRes when applied to obtain the solution of several linear systems of equations and in [20] it is shown that the QN-ILS method can be modified to become analytically equivalent to GMRes. A general comparison of various partitioned iterative solution methods for FSI is found in [21,22].

These algorithms are all designed to efficiently solve the coupled problem that results from an implicit time integration scheme applied to the semi-discrete system of equations describing the fluid and solid dynamics, the so called *partitioned* approach. The partitioned approach allows software modularity and reuse of existing field solvers and is therefore more promising in an industrial environment than the *monolithic* approach, which aims at solving the fluid and solid systems simultaneously. In the transonic regime, the flow interacts strongly with the structure since the flow is highly nonlinear and very sensitive to structural motions [23]. Especially for large time steps in the transonic regime, strong coupling procedures are necessary in order to avoid excessive phase-lag errors that would otherwise result from the dominating partitioning error [24]. Strong coupling algorithms are more expensive but unavoidable since loosely coupled algorithms yield unacceptable accuracy in this regime. It is this fact that motivates the development of more efficient partitioned strong coupling algorithms.

In this contribution we investigate the use of low fidelity models to speed up partitioned coupling simulations applied to high fidelity models, the so called *multi-fidelity* approach, see Fig. 1. Without loss of generality we assume that two solvers are available: a cheap low fidelity fluid solver and an expensive high fidelity fluid solver. We define a mapping between the input space of the low fidelity model and the input space of the high fidelity model during the coupling iterations: the space-mapping function. The space-mapping function keeps track of the differences between the high and low fidelity models during the coupling iterations which is subsequently used to speedup the computations. A-priori knowledge of the exact inverse space-mapping function would allow for the direct computation of the high fidelity solution by the inverse mapping of the low fidelity solution to the high fidelity space. However, such a-priori knowledge is not available. This necessitates the iterative approximation of the inverse space-mapping