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A stable second-order partitioned iterative scheme for freely vibrating low-mass bluff bodies in a uniform flow

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Abstract

We present a stable partitioned iterative scheme for solving fluid–body interaction problems at low structure-to-fluid mass ratio. The scheme relies on the so-called nonlinear interface force correction based on Aitken's extrapolation process to stabilize the coupled partitioned system employing an arbitrary Lagrangian–Eulerian finite element framework. Approximate interface force correction is constructed through subiterations to account for the missing effects of off-diagonal Jacobian terms in the partitioned staggered scheme. Through the generalized Aitken's geometric extrapolation process with a dynamic stabilization parameter, the interface corrections allow to satisfy the force equilibrium with arbitrary accuracy while expanding the scope of partitioned iterative schemes for fluid–structure interaction with strong added-mass effects. To assess the proposed iterative scheme against the standard strong coupling, effects of mass ratio are investigated for a freely vibrating circular cylinder. We show that our second-order scheme is stable for low mass density ratio and hence is able to handle strong added-mass effects. The numerical stability and robustness of the scheme is then demonstrated for a new application of tandem square cylinder undergoing complex wake-induced vibration and galloping.

Keywords: Interface force correction; Added mass effects; Subiteration; Aitken's process; Dynamic stabilization parameter; Wake-induced vibration

1. Introduction

Coupled dynamical fluid–structure systems exhibit a great variety of self-excited vibrations, both in useful and destructive manners. In particular, ocean environments are full of such self-excited vibrations, which constitute an interesting problem for the numerical modeling and can have a significant impact on the systems used in ocean and offshore engineering, including moorings, risers, subsea pipelines, large floating structures, and energy harvesting devices. In the dynamics of coupled fluid–body interaction, the phenomenon of frequency lock-in may occur for a given range of control parameters. The frequency of one system, e.g. fluid wake, deviates from its expected values

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while being close to the frequency of the another system, e.g. structure. In the absence of solid motion, the shedding frequency in the wake of a bluff body increases proportionally with the flow velocity according to the Strouhal law [1,2]. When the solid is let free to vibrate in cross-flow direction, a strong non-linear coupling between the motion and the wake dynamics exists. This results in a complex evolution of the shedding frequency which deviates from the Strouhal law as the natural frequency of the structure is approached, which is referred to as a lock-in of the wake frequency to the structural frequency. The lock-in range corresponds to a large amplitude oscillatory motion of the bluff body, which is of a practical importance in offshore and marine structures [3,4].

In the case of vortex-induced vibration, the frequency of unstable wake system approaches that of the oscillating bluff body which leads to an oscillating lift force with increasing amplitude of motion through a nonlinear resonance shift. The peak amplitudes and extent of lock-in, in terms of reduced velocity, is known to be significantly affected by the mass ratio between the structure and fluid systems. The upper limit of the extent of lock-in increases as the mass ratio from structure to fluid is decreased, which has been confirmed through experimental and theoretical studies. The authors [5,6] experimentally studied 2-DOF VIV of a circular cylinder at low mass ratios and reported a new response branch the so-called super-upper branch, which occurs when the mass ratio $m^* \leq 6$ in the turbulent regime. The peak vibration amplitude in the super-upper branch can go up to 1.5 times of the cylinder diameter.

For modeling the interaction of fluid flow with vibrating structures, ALE based simulations are generally accomplished by using either partitioned or monolithic schemes. A monolithic [7–10] approach assembles the fluid and structural equations into a single block and solves them simultaneously for each iteration. The fully-coupled finite-element formulation and implementation are discussed in details in [10]. The kinematic compatibility at the interface is achieved by construction, which leads to a reduction in the size of the linear system solved per nonlinear iteration. These schemes lack the advantage of flexibility and modularity of using existing stable fluid or structural solvers. However, they offer good numerical stability even for problems involving very strong added mass effects. In contrast, a partitioned approach solves the fluid and structural equations in a sequential manner, facilitating the coupling of the existing fluid and structural program with minimal changes. This trait renders the partitioned approach an attractive option from the computational point of view.

Typically, partitioned staggered schemes [11] are classified as either strongly-coupled (implicit) [12] or loosely-coupled [13,14]. Loosely-coupled (explicit) schemes satisfy the interface velocity continuity and traction continuity conditions in a sequential manner. These schemes often suffer from numerical instability and temporal inaccuracy caused by spurious energy production along the interface due to the time lag [15,16], and special treatments are generally required to address these issues. The numerical instability depends upon the material properties of fluid and structure and also on the relative geometric scales of the domain and the compressibility of the fluid. Notably, the sequential staggering introduces an explicit nature into the coupling even if both domains are solved implicitly. For an incompressible fluid interacting with low mass structures, reducing the time step size does not cure the instability regardless of whether the Courant condition for the individual domain is satisfied. This implies the instability is inherent in the sequential staggered scheme due to the strong nature of fluid–structure coupling [17–19]. A variety of force corrections and structural predictors [13,20] are used to increase the numerical stability of loosely-coupled schemes. Strongly-coupled schemes typically involve predictor–corrector subiterations to ensure the convergence of interface properties [21,22].

In several applications such as flow through blood vessels [18], ocean current interactions with offshore risers [23], strongly-coupled schemes suffer from convergence issues due to strongly predominant added mass effects. Theoretical closed-form findings of added mass force in [19,24] have clearly illustrated the difference between compressible and incompressible flow interacting with oscillating structure. For a model elastic plate, the added mass of a compressible flow system is proportional to the length of time interval, whereas the added mass of an incompressible system asymptotically approaches a constant value as the length of the time interval goes to zero. This finding has an implication in the design of fluid–structure coupling algorithms and the stability and convergence properties of the subiterations [25,23,17,21,18]. For large-scale FSI simulations, it is important to develop an efficient and general approach towards solving fluid flows coupled with flexible multibody dynamical structures. The flows can be modeled as fully incompressible or slightly compressible and can include turbulence effects. The structural components can comprise rigid bodies, solids, shells, beams and other elements including contact surfaces, gaps etc. For such large-scale flexible multibody dynamic interactions, monolithic formulations may require a substantial amount of effort and restructuring of the fluid and solid codes. On the other hand, partitioned procedures have desirable properties with regard to software developments, scalability and parallel processing.