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Parallel spectral difference method for predicting 3D vortex-induced vibrations

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ABSTRACT

This paper presents high-fidelity simulations of the vortex induced vibration (VIV) phenomena using a new computational model based on the high-order spectral difference (SD) method on 2D and 3D unstructured grids. The SD method constructs continuous fields within each cell with a Riemann solver to compute the inviscid fluxes at the cell interfaces and an averaging mechanism to compute the viscous fluxes. This method has shown promise in the past as a highly accurate, yet sufficiently fast method for solving unsteady viscous compressible flows on moving and deforming grids. A 4th-order, 5-stage Runge–Kutta scheme is used to advance time. In this viscous, compressible flow solver the displacement of an elastically mounted bluff body has been coupled to the lift force created by unsteady vortex shedding. The solver is validated against previously published numerical and experimental data for a single, elastically mounted cylinder. Preliminary studies into 2 cylinder wake galloping and determining the energy transfer coefficient have been performed and comparisons between 2D and 3D predictions have been made.

1. Introduction

1.1. Unsteady aerodynamic phenomena

When a structure or bluff body is subjected to fluid flow it is possible for it to undergo unintended vibrations due to aerodynamic instability phenomena. The main types of such phenomena are vortex induced vibrations (VIV), galloping, fluttering, and wake galloping [1]. VIV occurs when fluid flow over bluff bodies forms unsteady vortices on the trailing side of the body. As the vortices shed off of the body, oscillatory forces are applied to the body causing small amplitude vibrations of the body. If the oscillatory forces are applied at a frequency near the structure's natural frequency, resonance can severely increase the amplitude of vibration. This synchronization of frequencies is often called "lock-in".

Galloping and flutter occur when the derivative of the steady state lift coefficient is negative. As the structure oscillates in one direction, the lift forces generated by the body's shape decrease and become negative to pull it back. These types of phenomena are frequently called "diverging and self-regulating" since the structure's lift coefficient causes divergence from its resting place and eventually cause its return. In the case of flutter, this motion is accompanied by a torsional twist in the body, causing a pitching and plunging motion, as shown in Fig. 1. As the body lifts and twists, the torsional stiffness forces the body to twist back, causing a plunging motion.

Wake galloping occurs when multiple tandem bodies undergo VIV. The downstream bluff body is affected by the shedding wake from the upstream body. This can cause an increase in vibration amplitude in the downstream body. If the distance between the two bodies is too large (about 6 times the body diameter) or too small (about 2 times the body diameter) wake galloping may not occur [3].

1.2. Power of vortex induced vibrations

If the body is not designed properly, these phenomena can have disastrous effects. Historically, VIV (and its derivative forms) has been intentionally designed out of systems with prejudice due to the extreme destructive power displayed during engineering failures involving VIV. This power has been seen in simple cases such as water flowing past riser tubes bringing oil up from the seabed, flow around heat exchanger tubes, and in more famous cases such as the structural failure of Ferrybridge power station cooling towers in England which was resulted from VIV of turbulent flow [4] and the Tacoma Narrows Bridge collapse in 1940 which was caused by extreme flutter [5].

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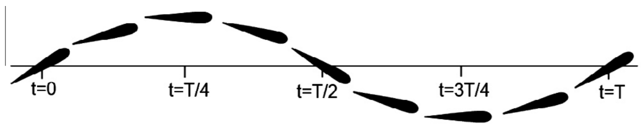

Fig. 1. Flutter aerodynamic instability phenomenon in an airfoil. As the airfoil lifts, the torsional forces twist the airfoil downward, causing a plunging motion [2].

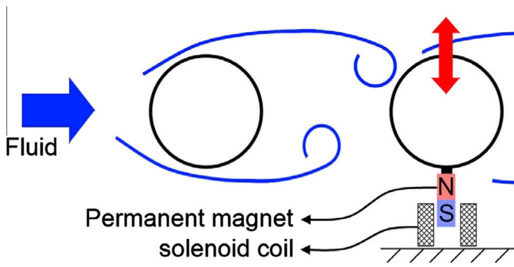

Fig. 2. Schematic of wake galloping energy harvesting method.

While engineering practice seeks to design out the VIV phenomena, there has been investigations into the possibility of using VIV as an energy harvesting technique. The work done by Shimizu [6], Bernitsas et al. [7], Kim [1], Assi et al. [8], and Jung and Lee [3] suggests that wake galloping can be used as a form of energy harvesting by converting the oscillations into electrical current, as seen in Fig. 2. Jung and Lee report a field test of a wake galloping device mounted on a bridge and Bernitsas et al. have been exploring the marketability of large scale VIV aquatic energy harvesters.

1.3. Existing studies of VIV

Given the destructive power of VIV and its potential as an energy harvesting technique, there has been considerable research into understanding the intense non-linear, unsteady, multi-dimensional flow that causes VIV. The experiments conducted by Feng in 1963 [9] are generally considered the first modern study of VIV. Feng introduces many of the concerns and questions about VIV which have still not been answered. Even though theoretical, experimental, and numerical research into VIV has been going on for decades, the fluid behavior and structural responses cannot be fully explained, only empirically predicted.

One of the main challenges is that VIV is extremely sensitive to the physical properties of the system. Making simple assumptions, such as only allowing vibrations in the plane normal to fluid flow, can cause wide divergence in results. Much of the research by Feng [9], Khalak and Williamson [10], Pan et al. [11], Zhao and Cheng [12], Zhoa et al. [13], and Ji et al. [14] has addressed a single cylinder in a cross flow current undergoing one-degree of freedom (dof) vibrations. In these studies, the cylinder is in some way restrained from vibrating parallel to fluid flow. However, VIV is inherently multi-dimensional and many situations in reality (such as suspension cables on bridges) do not display that constraint. Consequently, there have been 2 dof studies by Mittal and Kumar [15], Jeon and Gharib [16], Jauvtis and Williamson [17], and Prasanth et al. [18] which address body vibrations transverse and parallel to fluid flow. These researchers notice specific cases where the phase between the transverse and parallel oscillations is offset such that the cylinder moves in a circular, half-circular, or figure-8 motions, as shown in Fig. 3. In these cases the oscillations parallel to the fluid flow can affect the fluid–structure interaction, altering the transverse behavior.

For the flow conditions considered here, however, the parallel oscillations are orders of magnitude less that the transverse oscillations. Since one major application of this study is harvesting energy from the fluid flow, the smaller amplitude, parallel vibrations are of little interest (see Section 7). Hence only transverse oscillations are modeled in the numerical system studied herein.

In addition to the difficulty presented by the VIV sensitivity to physical properties and assumptions, a second problem is the wide range of variables to control. The above mentioned studies have observed extremely non-linear responses to varying free stream velocities, cylinder sizes, spring and damper coefficients, and Reynolds numbers. This is partly due to the coupling to two separate systems which are independently complex: unsteady, possibly transitional or turbulent fluid flow and a damped harmonic oscillator with non-linear applied loads. This highly variant, non-linear nature makes it difficult to create a single chart, table, or other medium to effectively communicate the cylinder response of each experiment. For example, a typical VIV amplitude response (A^*) for a variety of normalized flow velocities (U^*) can be seen in Fig. 4left). There are clearly three nonlinear regimes, namely the initial branch, lower branch, and upper branch. However, this only holds true if the mass-damping coefficient ($m^*\zeta$) is sufficiently small, in the order of 10^1. When m^* increases in the order of 10^2 the regimes shift, as shown in Fig. 4right) [19]. This is further complicated by intermittent and hysteretic switching between the branches for U^* near the singularities [20].

Although the non-linearity cannot necessarily be explained, it has been well established empirically. This allows numerical solutions to be compared to experimental results to validate their methods. To the best of the authors' knowledge, there is not yet any high-order model with the geometric flexibility to create a high-fidelity simulation of wake galloping systems used in VIV energy harvesters. Thus the present work investigates 1dof transverse vibrations in elastically mounted rigid cylinders using a novel, high order, parallel, 3D spectral difference (SD) solver. Incorporating moving and deforming unstructured grids allows the solver to analyze a wide variety of bluff body shapes and configurations, including square cylinders, tandem cylinders, or even clusters of parallel cylinders.

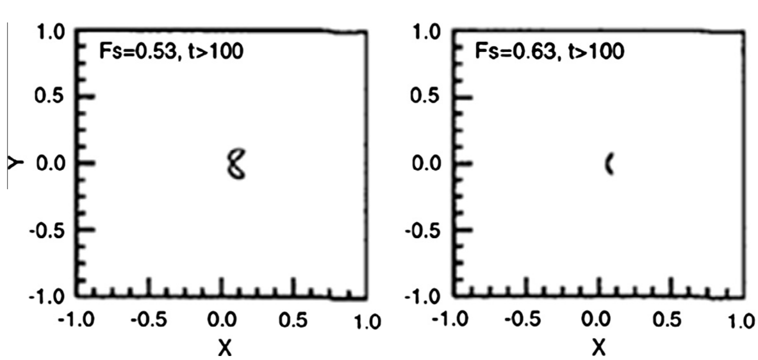

Fig. 3. *X–Y* plots for two studies of 2dof VIV where the cylinder oscillated in a figure-8 (left) and half-circle (right) [15].