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Evolution of an eroding cylinder in single and lattice arrangements

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ABSTRACT

The coupled evolution of an eroding cylinder immersed in a fluid within the subcritical Reynolds range is explored with scale resolving simulations. Erosion of the cylinder is driven by fluid shear stress. Kármán vortex shedding features in the wake and these oscillations occur on a significantly smaller time scale compared to the slowly eroding cylinder boundary. Temporal and spatial averaging across the cylinder span allows mean wall statistics such as wall shear to be evaluated; with geometry evolving in 2-D and the flow field simulated in 3-D. The cylinder develops into a rounded triangular body with uniform wall shear stress which is in agreement with existing theory and experiments. We introduce a node shuffle algorithm to reposition nodes around the cylinder boundary with a uniform distribution such that the mesh quality is preserved under high boundary deformation. A cylinder is then modelled within an infinite array of other cylinders by simulating a repeating unit cell and their profile evolution is studied. A similar terminal form is discovered for large cylinder spacings with consistent flow conditions and an intermediate profile was found with a closely packed lattice before reaching the common terminal form.

1. Introduction

Erosion due to flowing fluid occurs in a wide range of contexts. Wind erosion sculpt rocks, forming natural arches and other shapes dependent on the surrounding topology and rock properties. Yardangs are streamlined erosional wind forms (Ward, 1979; Ward and Greeley, 1984) whereas hoodoos are columns, pillars and toadstool rock forms (Scheidegger, 1958; Wang, 2005). These eroded rock formations affect the surrounding wind patterns which consequently influence the rock formations (Ward and Greeley, 1984; Scheidegger, 1958). Another example of this coupled effect between a fluid and solid body is river meanders (Leopold and Wolman, 1960); the naturally occurring curved paths of rivers. Simulations of streams with an initially straight channel have developed into these meandering patterns (Howard and Knutson, 1984). Erosion also features in biology with blood flows through arteries where plaque erosion and plaque rupture can be fatal (Farb et al., 1996). Ruptures often occur in regions of high wall shear stress τ_w upstream of the plaque (Groen et al., 2007). In this paper we examine the time evolution of an initially circular cylinder with both laminar and turbulent upstream conditions in high speed unidirectional flow (Reynolds number $\mathrm{Re} = 27000$) using numerical simulations. We find that the cylinder tends to a terminal form and then erodes self-similarly as found in experiments (Ristroph et al., 2012); dependent on the upstream conditions but independent of the initial or transitional shape.

Two modelling approaches exist for simulating the interface between phases: Eulerian (captures the boundary) and Lagrangian (tracks the boundary). The Eulerian approach is based on the immersed boundary method where the fluid and structure interaction (FSI) is modelled with the fictitious domains method and has been applied for cylinders in Stokes flow ($\mathrm{Re} \ll 1$, quasi steady flow) (Golay et al., 2011). However, this approach has difficulty in accurately modelling the fluid properties at the interface such as τ_w. The

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Lagrangian approach involves exclusively simulating the fluid phase and remeshing the computational domain as the interface deforms. This remeshing allows the standard meshing procedures for resolving near-wall velocity gradients to accurately capture surface features such as τ_w: either directly resolving the viscous sublayer or using wall treatment models. Recently, Mercier et al. (2014) have simulated erosion of soil from a turbulent jet using a 2-D axisymmetric model. They treated the flow as steady and used the $k-\epsilon$ and $k-\omega$ Reynolds averaged Navier-Stokes (RANS) turbulence models. However, remeshing is a computationally expensive task and their run times were one month with a cluster of 8 CPUs. We have used the Lagrangian approach because τ_w was selected as the driving mechanism of erosion and a highly resolved mesh near the boundary was sought to accurately simulate τ_w at this moderate Re.

We simulated the erosion of a circular cylinder in the subcritical flow regime at Re = 27000 with two types of configurations with particular attention to the fluid structure coupling. First, we simulated a single cylinder to validate our model against theory (Moore et al., 2013) assuming a laminar approximation and then against an experiment (Ristroph et al., 2012) using scale resolving simulations. Second, we investigated a lattice of cylinders which are sparsely separated and then a closely packed lattice where the flow transitions from shear layer reattachment (closely packed) to vortex shedding (smaller eroded cylinders with large spacings). There are no previous studies on simulating the erosion of a cylinder with unsteady turbulence in literature to the best of our knowledge, and nor dynamic meshing with a boundary deforming over such a significant change in curvature and scale.

2. Methods

2.1. Geometry and flow conditions

Flow over a cylinder was simulated with the same conditions as an experiment by Ristroph et al. (2012) to validate our model against, and a cylinder within a lattice of cylinders was also modelled. The cylinder eroded as a function of the local wall shear stress τ_w. The cylinder had an initial radius, $a_0 = 18$ mm, giving a Reynolds number, $\mathrm{Re} = 2u_\infty a_0/\nu = 27000$ where $u_\infty = 0.61$ m/s is the freestream velocity and $\nu = 8 \times 10^{-7}$ m^2/s the kinematic viscosity of water. This Re = 27000 is within the subcritical flow regime for a cylinder in cross flow where the wake is completely turbulent and there is a laminar boundary layer separation point on the top and bottom of the cylinder (Sumer and Fredse, 2006). Re scales linearly with a and typically reduces by a factor of four in our simulations and remains in this subcritical flow regime.

The Strouhal number is defined as

$$\mathrm{St} = \frac{2f_v a}{u_\infty} \tag{1}$$

where f_v is the vortex shedding frequency and is the inverse of the vortex period $T_v = 1/f_v$. The effective cylinder radius is time-dependent $a = a(t)$, reduces as the cylinder erodes and $2a$ is defined as the width of the cylinder (normal to flow). This characteristic length scale $2a$ controls the flow field behaviour including shedding vortex properties and Reynolds number.

Based on Prandtl boundary layer theory, the cross sectional area A of the eroding body follows a 4/3 power law in time t (Moore et al., 2013) with

$$A(t) \sim A_0\left(1 - \frac{t}{t_{\mathrm{end}}}\right)^{4/3} \tag{2}$$

where A_0 is the initial area and t_{end} the vanishing time of the body. The simulations were unable to reach t_{end} (where no material remained). Instead, a simulation-dependent final time t_f is defined where $t_f < t_{\mathrm{end}}$. The shear stress can be estimated as

$$\tau^* = \rho\sqrt{\frac{\nu u_\infty^3}{a}} \tag{3}$$

where $\rho = 998.2$ kg/m^3 is the density of the fluid (water, as per the experiment). The τ_0^* is a fixed characteristic stress and was used for non-dimensionalising.

Drag and lift coefficients were calculated as the total surface integral of the pressure and skin friction on the body. The projected areas, normal (for drag) and parallel (for lift) to the flow, are time-dependent and therefore these values were calculated for each mesh update.

The root mean square intensities of fluctuations in τ_w are greatest around the separation point (Yokuda and Ramaprian, 1990). This separation point θ_{sep} is where the τ_w vanishes as the boundary layer separates from the wall (Achenbach, 1968).

2.1.1. Single cylinder

A curvilinear O-type orthogonal grid was used with 50×100 (radial×circumferential) cells in the cross sectional plane as shown in Fig. 1a. Mesh nodes were clustered near the cylinder with $\Delta r/a_0 = 4 \times 10^{-3}$ for the first cell height giving $y^+_{\max} \approx 4$ throughout the simulations including the deformed mesh of the eroded cylinder. One spanwise cell was used to simulate the laminar 2-D case and 32 spanwise cells were used for the unsteady 3-D cases; this resolution of the spanwise flow features was indistinguishable compared with a 64 cell deep grid. The spanwise length was $8a_0$ which is adequate to accurately simulate the time-averaged statistics, as reasoned by Lysenko et al. (2014). The O-grid had an outer radius of $10a_0$ for the single cylinder cases giving 5×10^3 cells in 2-D and 1.6×10^5 cells in 3-D.