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On the limits of added-mass theory in separated flows and with varying initial conditions

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ABSTRACT

It remains unclear to what extent inviscid added-mass theory accounts for the forces exerted on an accelerating body subjected to separated flow. In this study, reactant forces and velocity-field data are systematically acquired using experimental measurements and simulations of an accelerating circular flat plate. Cases accelerated from rest are compared to cases accelerated from a steady flow state. When the added-mass forces predicted by potential theory and the resistance forces associated with the instantaneous plate velocity are accounted for, the remaining (residual) forces comprise approximately 20% of the peak force, even at high accelerations. In addition, the computed residual forces during accelerations both from rest and steady-state cases yield good collapse with respect to one another, indicating that the total forces are not a strong function of the initial state of the wake. These results suggests that inviscid added-mass theory is inadequate to predict the full reactant force even in the 'ideal' condition of impulsive motion from rest.

1. Introduction

Acceleratory motions are a ubiquitous feature of natural propulsion and are an important consideration in the design of many onshore and offshore structures as well. Offshore platform motions in particular have received much attention, and are the topic of investigations spanning many years (see for instance the comprehensive study by Sarpkaya and Isaacson (1981), where the current understanding of the forces in viscous flows are reviewed). The forces that arise when fluid accelerates around a body have classically been resolved into added-mass, viscous-drag, and flow-history contributions (Odar and Hamilton, 1964; Karanfilian and Kotas, 1978; Clift et al., 1978). The added-mass force, a concept derived from inviscid theory, has been the subject of numerous studies in recent years, primarily due to its relevance to propulsion and manoeuvrability (Weymouth and Triantafyllou, 2012, 2013; Polet et al., 2015). Determining whether added-mass is sufficient to account for reactant forces on bodies subjected to accelerations with separated flow is therefore of great practical interest.

Classical aerodynamic models proposed by Theodorsen (1935) and Küssner (1936), for instance, have prompted a contemporary force decomposition involving circulatory and non-circulatory (added-mass) effects. A few recent studies, such as Baik et al. (2012), have applied such a decomposition to the force histories of flat plates accelerating from rest. Pitt Ford and Babinsky (2013) predicted the non-circulatory lift on an impulsively-started flat plate at an angle of attack of 15° using a two-dimensional potential flow model coupled with values for the bound circulation that yielded the best

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agreement with the experimental measurements. They showed that the lift force produced by estimates of added mass was responsible for nearly half the lift during the acceleration period. The remaining lift force was attributed to circulation build-up in shed vortices, rather than bound circulation. Mancini et al. (2015) performed a similar analysis on surging flat plates at large angles of attack using the solution for the added-mass derived by Pitt Ford and Babinsky (2013) to determine the relative contributions of both the circulatory and non-circulatory effects. However, most studies have investigated reactant force decomposition for accelerations *from rest* (Prandtl and Tietjens, 1957; Manar et al., 2015; Babinsky et al., 2016), giving little attention to conditions in which the wake may already be strongly rotational. In addition, the argument in Leonard and Roshko (2001) extending potential-flow added-mass to general viscous flows hinges on a slip velocity applied at the body boundary, a concept which only applies in the limit of impulsive accelerations. While this may account for the need for a circulatory reactant force at finite accelerations, it has not been shown that this force goes to zero as the acceleration magnitude increases.

As such, the source of instantaneous forces exerted on bodies undergoing general acceleratory motions in a highly separated flow is still unresolved. To this end, this investigation acts as a benchmark study by providing an empirical decomposition of the forces encountered during accelerations. In particular, the present study is motivated by the diversity of initial conditions that may be encountered at the onset of acceleration. We focus on the applicability of added-mass theory in separated flows and aim to understand the influence of initial conditions on the added-mass coefficient. This is accomplished by comparing forces measured experimentally and from simulations to those predicted by potential-flow theory for a canonical test case. We decompose the instantaneous drag forces exerted on a circular flat plate for a range of accelerations including nearly impulsive motion, repeating the tests from rest and from ‘steady-state’ initial conditions. These two motions serve as extreme examples of kinematics encountered in nature and engineering, which severely violate assumptions of attached potential flow and therefore test the generality of added-mass force predictions. In addition, the circular flat-plate geometry is dominated by flow separation and has a known analytic potential-flow added-mass coefficient. It therefore provides a simple framework with which to systematically investigate the forces arising from different initial wake conditions. A number of previous studies have also focused on the circular flat plate as a benchmark test case – see for instance Tao and Thiagarajan (2003a,b) who investigated the vortex dynamics and resulting hydrodynamic forces on oscillating circular plates – which further increases the utility of the circular flat plate as a baseline geometry for continued characterization. While the results presented herein focus on the circular flat-plate geometry alone, the insight can be extended to more complex bodies subjected to flow separation during acceleratory motions. The presentation of the manuscript is as follows. In Section 2, the theoretical added-mass coefficient for a circular flat plate is discussed, followed by an outline of the experimental and numerical methods in Sections 3 and 4. Vortex evolution in the wake of the plate and the instantaneous drag forces are investigated in Section 5. Finally, the main conclusions of the study are summarized in Section 6.

2. The inviscid concept of added mass

The added-mass force can be solved algebraically for a variety of body shapes using potential theory once the time-varying velocity field is known. For a body translating at a constant speed (U) through a fluid, the kinetic energy of the body and surrounding fluid will also be constant, and proportional to the velocity squared. If the body begins to accelerate, then the kinetic energy in the surrounding fluid will increase. The time rate of change of the kinetic energy can be written in terms of the additional work that must be done by the body to increase the kinetic energy of the fluid (Brennen, 1982). For a circular flat plate accelerating normal to the fluid, the resulting added-mass force experienced by the body can be expressed as:

$$F_{AM} = \frac{1}{3}\rho D^3 a, \tag{1}$$

where F_{AM} is the added-mass force, ρ is the fluid density, D is the diameter of the plate, and a is the acceleration (Lamb, 1932). This equation can be arranged into the two Π-groups for force and acceleration as follows:

$$C_a = \frac{1}{3} = \frac{F_{AM}}{\rho D^3 a} = \left(\frac{F_{AM}}{\rho D^2 U^2}\right)\left(\frac{U^2}{aD}\right), \tag{2}$$

where C_a denotes the added-mass coefficient, and has a value of 1/3 for a translating circular flat plate. The inverse of the second dimensionless group is known as the acceleration modulus, defined as $a^* = aD/U^2$. Therefore, the normalized ratio of the added-mass force and the acceleration modulus returns the added-mass coefficient. Note that for a circular plate the definition of the drag coefficient is simply a scaled form of the force normalization given above:

$$C_d = \left(\frac{F}{\rho D^2 U^2}\right)\left(\frac{8}{\pi}\right). \tag{3}$$

It should be noted here that the Π-groups shown in Eqs. (2) and (3) are used to normalize the force data from the experiments and numerical simulations.

Fig. 1(a) provides qualitative streamline trajectories corresponding to the potential flow solution, from which the added-mass coefficient is derived, near the body of an accelerating circular flat plate. In a real, viscous flow it is uncertain