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Nonlinear modelling and control of the flow over aerofoils using CFD simulations

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ABSTRACT

A simulation based approach for nonlinear dynamical modelling and feedback control of the drag to lift ratio for aerofoils is investigated through case studies involving NACA 23012, ag13 and b737a aerofoils. The flow around the aerofoils is studied via numerical solutions of the 2D Navier–Stokes (NS) equations. A standard computational fluid dynamics (CFD) solver is extended to be able to measure desired feedback values and to apply a control input to the flow field. The proposed modelling and control approach is based on first determining the measurement points and injection points on the aerofoil for the control input. Then, to estimate the dynamical model, some input–output data are collected by injecting a chirp input flow to the field and saving the measurement data. Next a Hammerstein–Wiener (HW) type nonlinear dynamical model of the flow field is estimated using system identification. For control design, the nonlinear part of the model is eliminated by means of inverse functions, followed by the application of automated tuning methods to the linear part to obtain the closed-loop system. The results show that the designed feedback control system can reduce the drag to lift ratio considerably as compared to the unactuated case.

1. Introduction

While an accurate mathematical representation of fluid flows can be achieved using the Navier–Stokes (NS) partial differential equations, these are very difficult to analyse due to their complexity and most of the time obtaining an analytical solution is impossible [1]. As a result, flow systems are typically studied numerically using computational fluid dynamics (CFD) methods; examples include bluff body flows [2], forced convection heat transfer [3] and non-Newtonian flows [4].

Flow control strategies have been investigated for many years to manipulate fluid flow and change its behaviour to control relevant variables such as vorticity, lift, drag, transition, separation and so on [5]. Analysing the fluid flow around aerofoils is one of the important problems in fluid mechanics. One sample problem of interest is to control the separation on aerofoils, which is the breakaway or detachment of fluid from a solid surface. Studies about this topic include Liang et al. [6] who used two types of plasma aerodynamic actuation excited by microsecond discharge and nanosecond discharge and Greenblatt and Wygnanski [7] who proposed an experimental method of periodic hydrodynamic excitation to control the separation. Another significant problem is the analysis and manipulation of the lift and drag forces which are formed due to the geometry of the aerofoil and physical behaviour of the fluid flow around it [8]. In fixed wing aerial vehicles, the flight

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depends on the lift force which increases along with propulsion; however, high propulsion brings higher drag force [9]. To obtain more efficient flight, it is needed to overcome this trade-off. Achieving enough lift force to practice flight with less propulsion and drag force is an active field of research. Efforts towards increasing lift include Lee et al. [10] who proposed a multi-disciplinary design methodology and achieved a significant lift enhancement using micro-scale devices for turbine blades; Bai et al. [11] who used a flow deflector which can suppress the flow separation, delay the stall, and enhance the lift; Colonius et al. [12] who developed a method to control of the angle of attack of an aerofoil to enhance lift force; and Shojaefard et al. [13] who managed to increase the lift coefficient of an aerofoil with the help of blowing and suction. Enhancements through drag reduction have also received considerable research attention; studies in this direction include the work by Allan et al. [14] who used oscillatory flow excitation for the control of a generic model of an aerofoil, He et al. [15] who examined computational methods for active control and drag optimization of the incompressible viscous flow past cylinder, and Pastoor et al. [16] who investigated strategies for an elongated D-shaped body.

The goal of this study is to reduce the drag to lift ratio for aerofoils using active flow control based on nonlinear dynamical models obtained through system identification. A systematic methodology is developed and illustrated by case studies involving three commonly used aerofoils. This work complements the previous efforts of our research group on flow modelling [17,18], simulation [19,20] and control [21–23], while being unique in the sense that a systematic nonlinear modelling and control method for the flow around an aerofoil system based on unsteady incompressible flow data is developed and shown to yield successful results. The rest of this paper is organized as follows: Section 2 presents the problem description, Section 3 outlines the methodology, Section 4 discusses the results and Section 5 presents the conclusions.

2. Problem description

An aerofoil is the shape of an aircraft wing as seen in cross section. Fig. 1 shows the four main forces of flight acting on the aerofoil. The *weight* of the aircraft is directed downwards towards the earth. To achieve flight, the weight must be overcome by the *lift* force generated by the motion of the airplane through the air. The wing deflects the air downward and the opposite reaction pushes the wing up. The forward motion of the aircraft is attained by the *thrust* force generated by the engines. As the aerofoil pushes the air out of its way, the air pushes back on the aerofoil generating a *drag* force. This force is opposite to the motion direction and can be thought of as an aerodynamic friction. Wing structures are also used in boats, submarines and ships where the idea is similar but the fluid is water instead of air. When used in watercraft, these are often called *hydrofoils*.

The main goal of this study is to design a feedback control system to reduce the drag to lift (D/L) ratio (in other words to enhance the lift to drag (L/D) ratio) for flow over aerofoils using an actuator placed on the surface. To achieve this goal, a systematic method which consists of obtaining a nonlinear dynamical model by using system identification technique and designing a feedback controller system for the model is carried out for NACA 23012, ag13 and b737a aerofoils. The mesh structures constructed to be used for the computational fluid dynamics (CFD) simulations of these aerofoils are shown in Fig. 2, together with the points through which the actuators will be injecting or sucking fluid as necessary. The fluid flow is governed by the incompressible Navier–Stokes partial differential equations (PDEs)

$$\rho\left(\frac{\partial q}{\partial t}+(q\cdot\nabla)q\right)=-\nabla p+\mu\ \nabla^2 q$$
$$\nabla\cdot q=0 \tag{1}$$

where $\rho\in\mathbb{R}_+$ is the density of the fluid, $\mu\in\mathbb{R}_+$ is the dynamic viscosity of the fluid, $p(x,y,t)\in\mathbb{R}$ is the pressure and $q(x,y,t)=(U(x,y,t),\ V(x,y,t))\in\mathbb{R}^2$ is the flow velocity with u and v being the components in the streamwise and

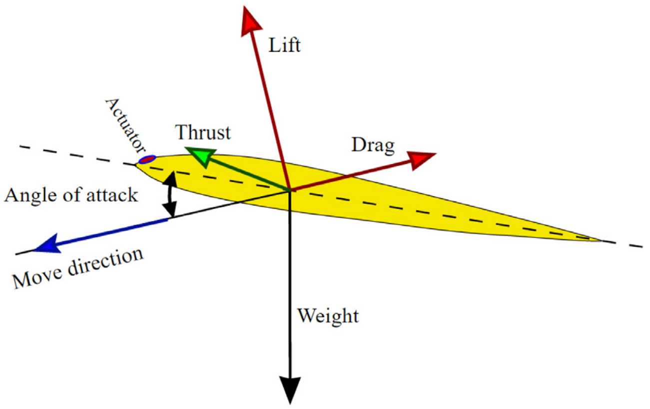

Fig. 1. Forces of flight on an aerofoil moving through a fluid [24]. The aim is to increase lift (L) and decrease drag (D), i.e. reduce the D/L ratio, using a small actuator placed on the surface.