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Assessment of spanwise domain size effect on the transitional flow past an airfoil

Wei Zhang*, Ravi Samtaney

Mechanical Engineering, Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, 4700 KAUST, Thuwal 23955-6900, Jeddah, Saudi Arabia

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ABSTRACT

In most large-eddy and direct numerical simulations of flow past an isolated airfoil, the flow is assumed periodic in the spanwise direction. The size of the spanwise domain is an important geometrical parameter determining whether the turbulent flow is fully developed, and whether the separation and transition patterns are accurately modeled. In the present study, we investigate the incompressible flow past an isolated NACA0012 airfoil at the angle of attack of 5 degrees and Reynolds number 5×10^4. The spanwise domain size L_z, represented by the aspect ratio $AR = L_z/C$ where C is the airfoil chord length, is varied in the range $0.1 - 0.8$. The effect of varying the normalized spanwise domain size AR is examined via direct numerical simulation (DNS) on several aspects of the turbulent flow quantities including the time-averaged and time-dependent behavior as well as the spanwise variation of the selected statistical quantities. DNS results reveal that different aspect ratios result in close predictions of the time-averaged aerodynamic quantities, and the velocity field except for a slight difference in the separation bubble. Smaller aspect ratios tend to underpredict the turbulent fluctuations near the separation point but overpredict them inside the separation bubble. Large differences are observed for multiple statistical quantities near the reattachment point, especially the turbulent kinetic energy budget terms. The leading edge separation is notably three-dimensional for simulation at $AR = 0.8$, while remaining quasi-2D for smaller aspect ratios. The spanwise two-point correlation coefficient shows significant dependence on the position of the probe and the velocity component analyzed: small aspect ratios do not produce uncorrelated results for all the velocity components. The simulation results demonstrate that examining only a few statistical quantities may result in a misleading conclusion regarding the sufficiency of the spanwise domain size. Reliable metrics to establish the sufficiency of spanwise domain size require thorough analysis of the turbulent statistics, and are necessary for three-dimensional simulation of turbulent flow in similar configurations.

1. Introduction

The computational fluid dynamics literature has numerous examples of two-dimensional Navier–Stokes simulations of flow past bluff and aerodynamically-shaped bodies. Usually, 2D simulations require fewer computational resources than corresponding 3D ones, and 2D results are physically relevant when the three-dimensionality effect is not of great concern as in cases where the spanwise size of the bluff body is sufficiently large, no spanwise forcing exists or simply when the Reynolds number is not large enough to amplify spanwise disturbances. 2D simulation results may also be good approximations of real flows in terms of the spanwise-average quantities. However, at high Reynolds number, the flow is intrinsically three-dimensional in nature, and only accurate 3D simulations can produce physically correct results. The spanwise size of the computational domain affects the simulation results, and a systematic investigation of spanwise size effect on the simulation quality is warranted.

Comparisons between experimental and numerical studies have shown that for flow past bluff bodies, the spanwise coherence of the vortices may be artificially reinforced in 2D simulations [1] and thus the validity of such results is questionable. In 3D simulations the spanwise domain size, representing the separation distance between end plates in experiments or the length of the bluff body in simulations, is normalized and represented by the aspect ratio $AR = L_z/L_{ref}$, where L_z is the spanwise domain size and L_{ref} is a reference length (cylinder diameter D or airfoil chord length C, etc.). In experiments the bluff body is usually held by the two end plates in a wind or water tunnel. The flow past such a bluff body is affected by the growth of the boundary layer on the plates, indicated by the non-uniformity of the measured quantities along the spanwise direction and oblique

* Corresponding author. Tel.: +9660128082246.
E-mail addresses: wei.zhang@kaust.edu.sa, xjtuzhangwei@qq.com (W. Zhang), ravi.samtaney@kaust.edu.sa (R. Samtaney).

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shedding of vortices. In numerical simulations the no-slip boundary condition constraint due to the end plates is usually relaxed by imposing slip or periodic boundary condition in the spanwise direction, with the expectation that the result is a closer approximation of flow in an infinite domain.

The spanwise domain size is a key geometric parameter in modern direct numerical simulation (DNS) and large-eddy simulation (LES) studies of flow past bluff bodies. It not only determines the accuracy of fluctuating aerodynamic forces but also the turbulent statistics (e.g., [2,3]). Earlier studies (e.g. [4]) have shown that even for low-Re flow, the stochastic fluctuations of aerodynamic forces are accompanied by both low- and high-frequency modulations, which are suppressed in 2D simulations or 3D simulations with small aspect ratio where perfect periodic variations are normally observed. For the example of a flow past a cylinder, the aerodynamic forces acting on the cylinder are significantly affected mainly due to the inaccurate prediction of the surface pressure [5]. These examples provide a motivation for a systematic investigation of spanwise domain size effect in numerical (and also experimental) studies of flow past bluff bodies and similar configurations. In the present work we will narrow our review and investigation on the spanwise domain size effect for an isolated airfoil under certain parameters, rather than a comprehensive study that covers a large parameter space.

1.1. Flow past an isolated airfoil: experiment

Compared with the isolated cylinder, the airfoil is a streamlined geometry, and consequently the flow separation and transition patterns are different. For incoming laminar flow past a nominally two-dimensional airfoil (i.e., without spanwise skewness), the separation and transition patterns are complex and are strongly dependent on the angle of attack (AoA) and the Reynolds number. The low-Re flow (Re $<$ 70,000 by Lissaman [20] and $\sim$15,000–500,000 by Mueller & DeLaurier [21]) past an airfoil shows detachment close to the leading edge due to the adverse pressure gradient (APG) field; the separated flow is unstable and transitions rapidly to turbulence. At high AoA the turbulent flow remains detached from the airfoil surface, whereas at lower AoA it may reattach to form a turbulent boundary layer and the well-known laminar separation bubble [22]. The turbulent flow downstream of the airfoil trailing edge is relatively fully developed into the turbulent regime, hence turbulent fluctuations must be taken into account and the spanwise domain size should be sufficiently large to resolve the largest flow structure in this direction.

We summarize the key parameters in selected experimental studies of flow past an airfoil in Table 1. The incoming flow is normally of low turbulent intensity and transition is expected to occur above the airfoil suction surface. In experiments the two end plates supporting the airfoil in the wind tunnel affect the flow in the middle of the tunnel because of the boundary layers formed on them, and hence these end plates should be placed far away from each other to minimize any interference. It is seen in the table that the aspect ratio of the airfoil is normally larger than 1.0, which is larger than most simulation studies. Boutilier & Yarusevych [6] investigated the effect of the end plates on flow past a NACA0018 airfoil at Re $= 10^5$ and AoA $=$ 0–15 degrees, and found that the existence of the end plates improves the mean spanwise uniformity. The separation distance between the two end plates, i.e., the aspect ratio used in this paper, does not affect the frequency of the vortex shedding, and a smaller AR reduces the spanwise coherence of the wake vortices. Based on their experimental results, the authors recommended that AR $\geq 7.0C\sin(\text{AoA})$ should be used to minimize the end plates effect on the mean quantities at the mid-span plane of the airfoil where measurements are taken. Burgmann *et al.* [10] studied the flow past a SD7003 airfoil at Re $= 2 \times 10^4$ and AoA $=$ 4–8 degrees, and found that the thickness of the boundary layer on the water tunnel walls is about $0.05C$ at the position of the airfoil, which is roughly $2C$ from the inflow plane, and is believed to have no effect on the flow field at the airfoil mid-span. In the experiment the aspect ratio is 1.5 and the horseshoe vortices do not affect the flow field at the mid-span. Hain *et al.* [12] performed comparative experiments at AR $=$ 1.25 and 2.5 for flow past the SD7003 airfoil at Re $= 6.6 \times 10^4$. Both experiments show that there is no strong mean spanwise velocity at the airfoil mid-span, reflecting the negligible effect due to the end plates.

We conclude from the above discussion and the summary in Table 1 that the end plates effect is a crucial concern in experimental studies of flow past an isolated airfoil. Generally, for flow at Reynolds number higher than 10^4, the boundary layer thickness is small and has only negligible effect on the flow field at the airfoil mid-span, e.g., through the formation of horseshoe vortices at the ends of the airfoil. However, the end plates do affect the spanwise uniformity of the flow field, in time-averaged and time-dependent senses, thus the aspect ratio of the airfoil has to be chosen with care.

1.2. Flow past an isolated airfoil: simulation

Numerical simulations of flow past an isolated airfoil, especially DNS and LES, are performed to investigate the physics of the separation, transition and development of the flow over the airfoil. Usually the end plate effect, due to its physical complexities, is not modeled. Instead, the usual choice is the application of periodic boundary condition in the spanwise direction to model an airfoil with large aspect ratio in an infinite medium. In these simulations, it is required that

Table 1
Summary of selected experimental studies on flow past an isolated airfoil or inclined flat plate. The abbreviations are: HW-Hot Wire; PP-Pressure Probe; PIV-Particle Image Velocimetry; LDA-Laser Doppler Anemometer; HFA-Hot Film Anemometry; PTV-Particle Tracking Velocimetry; SWV-Smoke Wire Visualization.

Source	Airfoil	Method	$Re/10^4$	AoA	AR
Boutilier & Yarusevych [6]	NACA0018	HW,PP	10	0–15	0.5–2.5
Boutilier & Yarusevych [7]	NACA0018	HW,PP	5–25	0–21	2.0
Boutilier & Yarusevych [8]	NACA0018	HW,PP	10	0–15	3.0
Buchmann *et al.* [9]	NACA0015	PIV	3	18	5.0
Burgmann *et al.* [10]	SD7003	PIV	2	4–8	1.5
Ghaemi & Scarano [11]	NACA0012	PIV	38.6	0	1.0
Hain *et al.* [12]	SD7003	PIV	6.6	4	1.25
Hu & Yang [13]	GA(W)-1	PP,PIV	7	6–14	3.0
Lam [14]	Flat plate	LDA	3	30	11
Nakano *et al.* [15]	NACA0018	PIV	16	0–9	2.38
Packard *et al.* [16]	NACA64$_3$-618	PIV,HFA	6.4	-1-20	1.0,2.37
Suzuki *et al.* [17]	NACA0012	PTV	0.1	15	2.86
Yarusevych *et al.* [18]	NACA0025	HW,SWV	5.5–20	0–10	3.03
Zhang *et al.* [19]	SD7003	PIV	2,6	4	1.25