Computers and Fluids 146 (2017) 117–124

Contents lists available at ScienceDirect

Computers and Fluids

journal homepage: www.elsevier.com/locate/compfluid

Direct numerical simulations of the flow around wings with spanwise waviness at a very low Reynolds number

D. Serson[a,b,*], J.R. Meneghini[b], S.J. Sherwin[a]

[a] Department of Aeronautics, South Kensington Campus, Imperial College London, SW7 2AZ, UK
[b] NDF, Escola Politécnica, Universidade de São Paulo, Av. Prof. Mello Moraes, 2231, São Paulo, 05508-030, Brazil

ARTICLE INFO

Article history:
Received 21 March 2016
Revised 22 December 2016
Accepted 16 January 2017
Available online 17 January 2017

Keywords:
Incompressible flow
Spectral/hp methods
Flow control

ABSTRACT

Inspired by the pectoral flippers of the humpback whale, the use of spanwise waviness in the leading edge has been considered in the literature as a possible way of improving the aerodynamic performance of wings. In this paper, we present an investigation based on direct numerical simulations of the flow around infinite wavy wings with a NACA0012 profile, at a Reynolds number $Re = 1000$. The simulations were carried out using the Spectral/hp Element Method, with a coordinate system transformation employed to treat the waviness of the wing. Several combinations of wavelength and amplitude were considered, showing that for this value of Re the waviness leads to a reduction in the lift-to-drag ratio (L/D), associated with a suppression of the fluctuating lift coefficient. These changes are associated with a regime where the flow remains attached behind the peaks of the leading edge while there are distinct regions of flow separation behind the troughs, and a physical mechanism explaining this behaviour is proposed.

1. Introduction

The possibility of using wings with a wavy leading edge as a way of obtaining improved aerodynamic performance started receiving attention after the work of Fish and Battle [3], where the morphology of the pectoral flipper of the humpback whale (*Megaptera novaeangliae*) was analysed with a focus on its hydrodynamic performance. These flippers have protuberances on the leading edge, and this was suggested to act as a mechanism to delay the stall, allowing the flipper to maintain a high lift coefficient at high angles of attack, giving the whale a good maneuverability.

The idea that leading edge protuberances could delay stall gained support with the work of Miklosovic et al. [9,10]. They presented experiments for full-span and half-span wings with a NACA0020 profile in configurations with and without leading edge waviness. For the half-span model, which had a planform similar to the flipper of the humpback whale, the Reynolds number was around 6×10^5 and the modified wing led to an increase in the stall angle. This increase in the stall angle contributed to an increase in the maximum lift coefficient of the wing. However, for the full-span model, for which the Reynolds number was around 2.7×10^5, their results show that the protuberances lead to a premature stall, being beneficial only in the post-stall regime. Also, the experiments for full-span wings presented in [5] showed the same behaviour, with the modified leading edge causing a premature stall.

Although these first studies about the effect of leading edge protuberances showed a strong distinction between the behaviour of full-span and half-span models, more recent works suggest that the main factor affecting the results is the Reynolds number. First, Stanway [14] presented experiments for a model similar to the half-span wing of Miklosovic et al. [10], but considering different values of Re between 4×10^4 and 1.2×10^5. Only for the highest value of Re considered the waviness caused an increase in the maximum lift coefficient, indicating that the value of Re has an important role in determining whether the use of wavy leading edges will improve aerodynamic performance. Another study which supports the importance of the Reynolds number effect on this flow is that of Hansen et al. [4]. They performed experiments with rectangular wing mounted in both full-span and half-span configurations, in an attempt to isolate the influence of the wing tip on the results. The effect of using a wavy leading edge was similar in both cases, indicating that three-dimensional effects related to the wing-tip have a secondary importance in the effectiveness of the waviness.

Despite the significant number of studies on this problem, a definite explanation to how the leading edge waviness affects the

* Corresponding author.
E-mail addresses: d.serson14@imperial.ac.uk (D. Serson), jmeneg@usp.br (J.R. Meneghini), s.sherwin@imperial.ac.uk (S.J. Sherwin).

http://dx.doi.org/10.1016/j.compfluid.2017.01.013
0045-7930/

flow is still absent. In this paper, an extensive study based on direct numerical simulations is presented for the flow around infinite wavy wings with a NACA0012 profile at $Re = 1000$. Although this Reynolds number is much lower than most practical applications, it is our belief that the conclusions presented here can help in the understanding of the mechanisms responsible for the behaviour observed at higher Reynolds numbers.

The paper is organized as follows. Section 2 briefly presents the numerical methods and describes the setup employed in the simulations. Then, Section 3 presents the results, and finally Section 4 contains the conclusions of this work.

2. Problem formulation

2.1. Numerical methods

We consider an incompressible viscous flow, which is governed by the Navier–Stokes equations. Assuming a unit density, these equations can be written as:

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u}\cdot\nabla)\mathbf{u} - \nabla p + \nu\nabla^2\mathbf{u},$$
$$\nabla\cdot\mathbf{u} = 0, \tag{1}$$

where $\mathbf{u}$ is the velocity, p is the pressure, and ν is the kinematic viscosity. Taking the chord c as reference length and the free-stream velocity U_∞ as the reference velocity, the Reynolds number is defined as $Re = \frac{cU_\infty}{\nu}$.

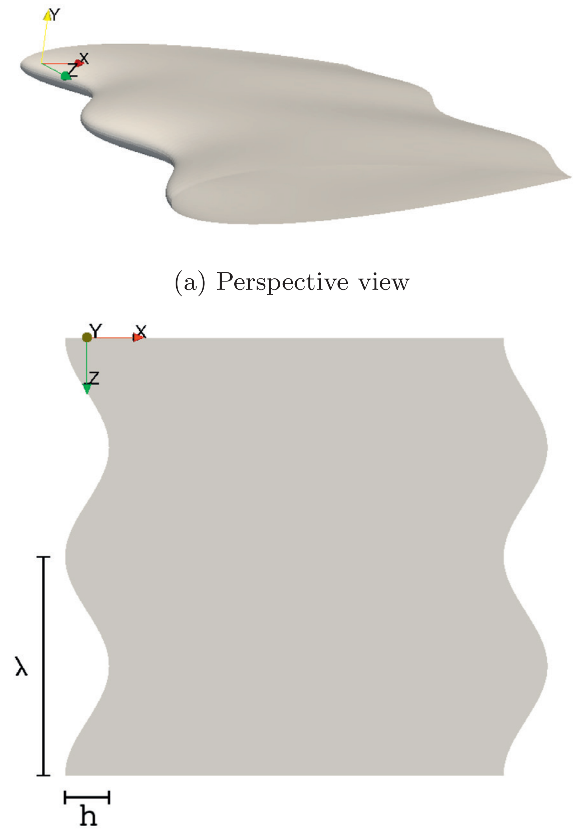
The waviness of the wing was treated by a coordinate system transformation using the formulation proposed in [12], so that the wavy geometries were mapped into the straight wing. Then, the equations were discretized following the Spectral/hp method presented in [8], with the span direction discretized using a Fourier expansion, as proposed by Karniadakis [6]. The use of a Fourier expansion in the third direction is an efficient way of studying an infinite wing with periodic boundary conditions, and was only possible because of the simplification in the geometry provided by the coordinate transformation. The equations were then solved by time integration using the stiffly stable splitting scheme described by Karniadakis et al. [7].

2.2. Simulations setup

All numerical simulations presented here were performed for $Re = 1000$, using a modified version of the incompressible Navier–Stokes solver encapsulated within the spectral/hp element code Nektar++ [1]. The geometries are based on a NACA 0012 profile, with a small modification to obtain a zero-thickness trailing edge, since the small thickness of the trailing edge in the original profile would lead to meshing challenges. The wavy geometries were obtained by applying the following coordinate transformation to the straight infinite wing:

$$\bar{x} = x + \xi(z) = x - \frac{h}{2}\cos\left(\frac{2\pi}{\lambda}z\right). \tag{2}$$

where h is the waviness peak-to-peak amplitude, λ is its wavelength, $\bar{x}$ is the physical coordinate in the chord direction, and x and z are the chord wise and span wise coordinates in the computational domain. Fig. 1 shows an example of a geometry obtained through this transformation, identifying the waviness parameters and the orientation and origin of the coordinate system. Note that this transformation deforms both the leading and the trailing edges, and has no effect on the chord. This type of transformation was preferred because it leads to a simpler procedure when solving the equations with the mapping [12]. However, in Section 3.5 we relax this restriction by considering the effect of waviness in the leading edge and in the trailing edge independently. As will be seen, the transformation from Eq. (2) leads to results that are equivalent to deforming only the leading edge, as is usually the case in the literature.



(a) Perspective view

(b) Planform

Fig. 1. Geometry of a wavy wing with $h/c = 0.1$ and $\lambda/c = 0.5$.

Table 1
Parameters of the waviness for the cases analysed

Case	λ/c	h/c
Baseline	–	0.0
L025h0125	0.25	0.0125
L025h025	0.25	0.025
L025h05	0.25	0.05
L05h025	0.5	0.025
L05h05	0.5	0.05
L05h10	0.5	0.1
L10h05	1.0	0.05
L10h10	1.0	0.1
L10h20	1.0	0.2

We considered the case without any waviness (referred to as baseline) and wavy geometries with nine different combinations of the parameters λ and h. These cases are summarized in Table 1, where a naming convention is also introduced. The parameters were chosen taking into account the range of parameters encountered in the literature [2,4], with the amplitudes adjusted according to the wavelength in order to have the same ratios $\frac{h}{\lambda}$ for each wavelength.For each case, simulations were performed for angles of attack between $\alpha = 0^\circ$ and $\alpha = 21^\circ$, at increments of $\alpha = 3^\circ$.

For all simulations the spatial discretization in the xy plane consisted of a mesh with 550 quadrilateral elements, with the solution represented by 8th order polynomials inside each element. This mesh, which is shown in Fig. 2, extends from $-10c$ to $10c$ in the chord direction x, and from $-15c$ to $15c$ in y. The z di-