Numerical study of low Reynolds number airfoil flows

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A numerical study of the flow and acoustic field around low Reynolds number NACA0012 airfoils is presented in this work. Unsteady flow fields are computed by solving the 2D compressible Navier Stokes equations using low-dispersion and low-dissipation optimized finite-difference schemes. The chord based Reynolds number of the airfoil is varied between 15,000 and 50,000, for angles of attack in the range 0 to 4 degrees and for Mach numbers between 0.15 and 0.5. Numerical velocity, wall pressure and far field acoustic results are compared to those of various DNS in the literature. Strouhal number scaling of the vortex shedding in the wake is illustrated, and acoustic scaling of the trailing edge noise as a function of Mach number is examined. Effects of airfoil incidence on far field noise levels and directivity are also presented.

1 Introduction

It is well established that airfoils in low to moderate Reynolds number flow conditions are liable to produce tonal acoustic sound fields. However the detailed mechanisms responsible for such tonal noise generation remain subject to debate. Since the work of Paterson *et al* [7], general trends for tonal frequency as a function of flow speed have been established. A number of experimental studies have focused on NACA 0012 airfoils with Reynolds numbers in the range of 1.5×10^5 to 3×10^6. Recently, a few numerical computations have also been reported for airfoils at moderate Reynolds numbers. There is however little data, be it experimental or numerical, for low Reynolds numbers smaller than 10^5. This work provides a number of additional data points, at Reynolds numbers below those often studied and at varying Mach numbers, and confronts their results to models generally applied to higher Reynolds numbers.

2 Numerical details and configurations

In this work, the 2-D Navier-Stokes equations are solved on a computational grid which is obtained from the body-fitted grid by applying a suitable curvilinear coordinate transformation. A detailed presentation of the transformed equations, as well as examples of benchmark problems performed with the solver, can be found in Marsden *et al.* [5]. The body-fitted grid is of C-type, as shown in figure 1, and caution is exercised during its generation in order to obtain grid lines of maximal regularity. In the airfoil's wake, there is a collocated grid overlap zone, avoiding the need for interpolation in this region.

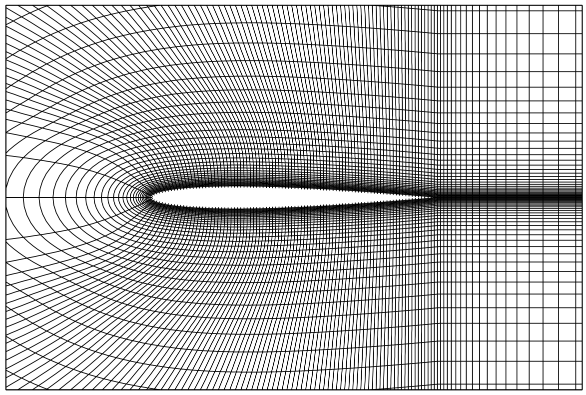

Figure 1: Typical C-type grid around the NACA 0012 airfoil. Every fifth grid line is shown.

The equations are solved with an optimised high order numerical procedure, involving explicit finite differences, centred where possible and non-centred close to boundaries, as well as explicit sharp cut-off filters, again both centred and non-centred [4, 3]. Time advancement is performed thanks to a six-step optimised Runge-Kutta algorithm.

The airfoil studied here is a NACA0012, whose final coefficient is modified in order for the trailing edge not to be truncated. Reynolds numbers in the study range from 20,000 to 50,000, Mach numbers from M=0.15 to M=0.5, and the airfoil chord c from 2×10^{-3} to 6×10^{-3} mm. A total of 1500 grid points in the curvilinear direction and 400 in the radial direction are used in all the computations. The computational domain extends out roughly ten chords in each direction from the airfoil.

3 Results

The computational code was tested on low Reynolds number airfoils by comparing results with those of Sandberg *et al.* [8] for an airfoil at a Mach number of 0.4, a Reynolds number of 50000 and at an incidence of 5° to the incoming flow. A good qualitative and quantitative match is obtained. An illustration of this match is provided in figure 2 which shows vorticity contours from Sandberg's computation, and those from the present work at identical parameters immediately below.

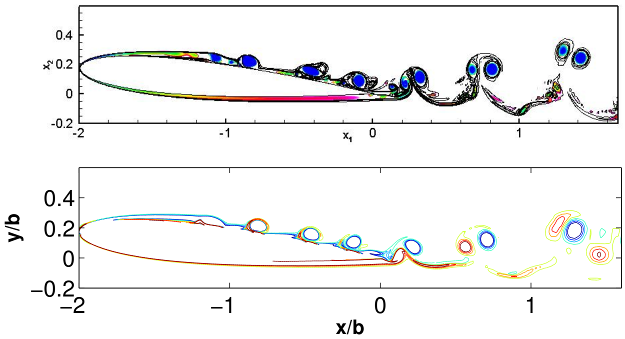

Figure 2: Contour lines of instantaneous vorticity field for a NACA 0012 airfoil at Re=50×10^3 and M=0.4. Top: figure from Sandberg et al., bottom: present work.

In almost all the computations performed for this work, a tonal frequency is detected. This provides additional data points to those found in the literature, in particular for very low Reynolds numbers. Figure 3 summarizes experimental and numerical data from various researchers regarding the presence of a tonal noise as a function of the Reynolds number and angle of attack. The solid line represents an estimation provided by Lowson (1994) of the zone in which tonal noise is generated. It can be noted that below Reynolds numbers of 50,000, there is no experimental data available, and thus it is not known experimentally whether such flow configurations should generate tones or not. Table 1 lists the configurations studied here, as well as the presence or not of a far field tonal noise component.

At the lowest flow Reynolds number of 17.4×10^3, a tone is already observed. This is illustrated in figure 4 which presents snapshots of the vorticity and pressure fields around the airfoil. At this very low Reynolds number, the boundary layers are almost perfectly steady, and it is only in the wake that flow unsteadiness is observed. A number of researchers have proposed that there is an absolute instability in the wake of NACA 0012 airfoils [6, 9], which could explain the vortex shedding observed in this case.

Tonal frequency is observed to increase, as expected, with flow Mach number. Frequency variation is well predicted by $f \sim M^{1.5}$, as shown in figure 5, as proposed by Paterson [7], albeit with a larger constant of $K = 0.02$. The number of flow speeds studied here is insufficient to ascertain whether a ladder-like struc-

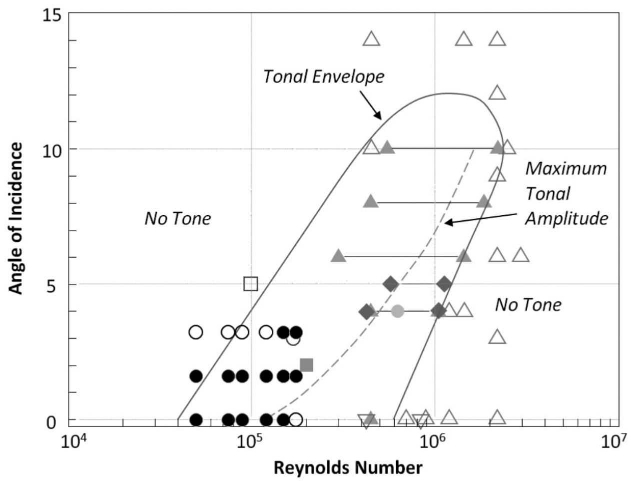

Figure 3: Pattern proposed by Lowson et al. (1994) in which the tonal noise phenomenon is likely to occur. Filled symbols indicate the presence of a tone, while empty symbols indicate no tone was detected. Experimental data from various works. Figure from Arcondoulis et al. [2]

M	0.15	0.2	0.2	0.2	0.2	0.2
Re	17.4	23.2	23.2	23.2	23.2	23.2
α	0	0	1	2	3	4
tone	○	○	○	○	○	
M	0.25	0.3	0.3	0.3	0.35	0.35
Re	29	34.8	23.2	34.8	40.6	40.6
α	0	0	0	1	0	1
tone	○	○	○	○	○	○
M	0.4	0.4	0.5	0.5		
Re	46.4	50	58	23.2		
α	0	5	0	0		
tone	○			○		

Table 1: Mach number, Reynolds number $\times 10^{-3}$ and angle of attack for the present computations , as well as presence (○) or not of tonal acoustic radiation.

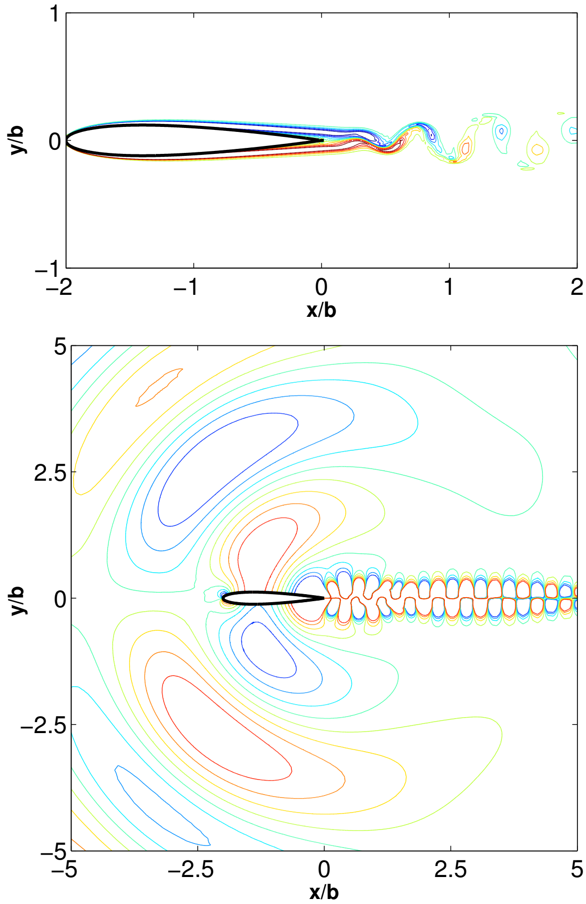

Figure 4: Instantaneous vorticity and pressure fields at M=0.15 and Re=17.4×10^3*. Colour scales between* $\pm 20U_\infty/c\, s^{-1}$ *for vorticity and* ± 3 *Pa for pressure*

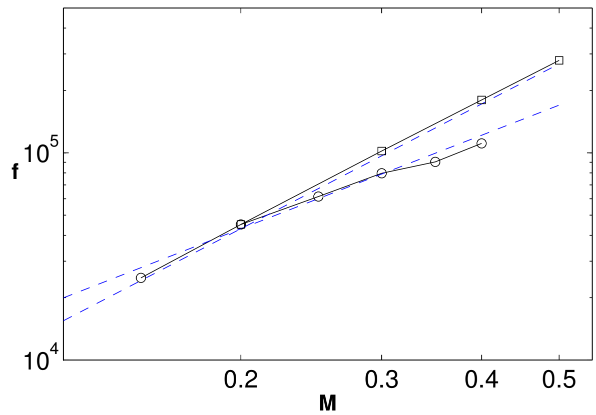

Figure 5: Frequencies as a function of Mach number at zero angle of attack, $\circ$ *for an airfoil of chord* $c = 5 \times 10^{-3}$ *m and* $\square$ *for an airfoil at a constant Reynolds number of* 23.2×10^3*. Dotted lines correspond to Paterson's formula with* $K = 0.02$*.*

ture in the acoustic frequencies, such as that observed by Paterson [7] and by Arbey and Bataille [1].

Sound pressure level also increases with flow Mach number, with a large power dependence on M. This is illustrated in figure 6, which provides SPL as a function of Mach number both for an airfoil of constant chord and one of constant Reynolds number. For the constant Reynolds case, the SPL increases roughly with the 7^{th} power of the velocity, while that for the constant chord case increases more rapidly still, in particular for M=0.3 and above. The steady nature of the boundary layers for the very low Reynolds numbers may explain the very large difference in noise levels at higher Mach numbers. Reynolds number effects at a Mach number of 0.4 are highlighted in figure 7. Vorticity snapshots are presented for Reynolds numbers of 23.2×10^3 and 46.4×10^3 in the vicinity of the trailing edge. Unsteady vorticity crossing the trailing edge is observed to be nearly 5 times higher in the high Reynolds case than in its low Reynolds counterpart, which matches the difference of 10 dB found between their acoustic fields quite well. The very sharp increase in acoustic radiation found for an airfoil at Mach numbers above 0.3 seems also to have been observed experimentally by Arcondoulis *et al* [2], who found that this trend stopped for Reynolds numbers above 75,000.

A more detailed examination of flow configurations with non-zero angle of attack is currently under-

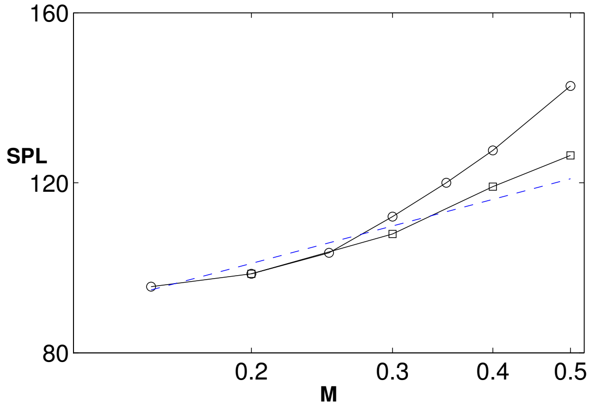

Figure 6: Sound Pressure Level as a function of Mach number at zero angle of attack, ○ for an airfoil of chord $c = 5 \times 10^{-3}$ m and □ for an airfoil at a constant Reynolds number of 23.2×10^3, at a distance of 4 chord lengths from the trailing edge perpendicular to the airfoil. Dotted line corresponds to M^5 scaling .

way.

4 Concluding remarks

A study of very low Reynolds number airfoil flows has been conducted. Results show that tonal acoustic radiation is generated well below Reynolds generally found in low-Reynolds-number experiments, for zero or small angles of attack. As in the case of higher Reynolds numbers, an increase in angle of attack tends to destroy the tonal nature of the acoustic field. Tonal frequencies appear to be well predicted by the Paterson formula.

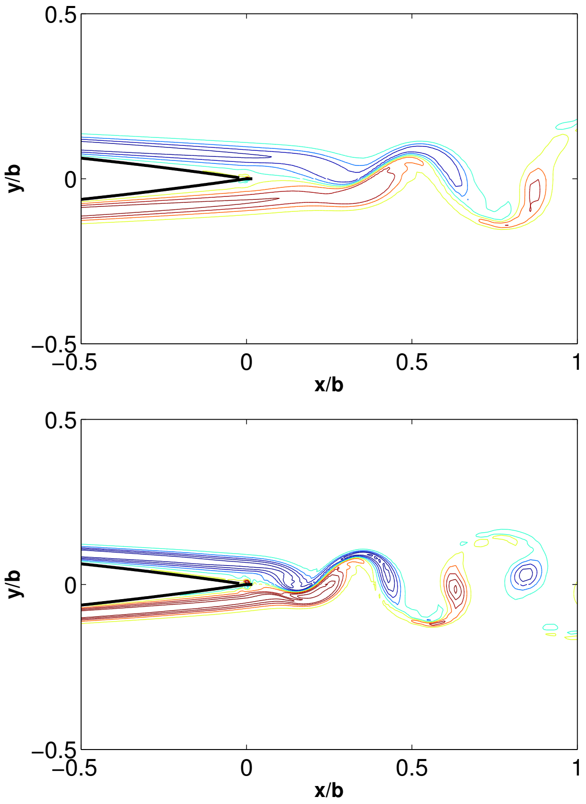

Figure 7: Vorticity snapshots at (top) Re=23.2×10^3 and (bottom) Re=46.2×10^3.

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