Experiments in Fluids (2005) 38: 545–547
DOI 10.1007/s00348-005-0943-2

SHORT COMMUNICATIONS

S. Yarusevych · P. E. Sullivan · J. G. Kawall

Airfoil boundary layer separation and control at low Reynolds numbers

Received: 17 March 2004 / Revised: 17 January 2005 / Accepted: 27 January 2005 / Published online: 15 March 2005

Abstract The boundary layer separation on a NACA 0025 airfoil was studied experimentally via hot-wire anemometry and surface pressure measurements. The results provide added insight into periodic boundary layer control, suggesting that matching the excitation frequency with the most amplified disturbance in the separated shear layer is optimal for improving airfoil performance.

1 Introduction

Laminar boundary layer separation often takes place on the upper surface of an airfoil operating at low Reynolds numbers, e.g. Mueller and DeLaurier (2003). Transition to turbulence occurs in an unstable separated shear layer and can result in boundary layer reattachment and the formation of a laminar separation bubble. It should be noted that laminar boundary layer separation significantly affects airfoil performance, reducing lift and increasing drag. The behaviour of the separated shear layer and the extent of the separation region are major factors determining the severity of this effect.

It is possible to improve airfoil performance by means of periodic excitation. Previous work by Zaman (1992) and Yarusevych et al. (2003) show that optimum values of the control parameters may be correlated with the airfoil boundary layer and/or wake characteristics. However, various experimental attempts to predict optimum values of excitation parameters, summarised by Zaman (1992), have resulted in contradictory conclusions.

The main objective of the present work is to gain insight into the flow control mechanism responsible for improved airfoil performance by periodic excitation.

2 Experimental description

The performance of a symmetrical NACA 0025 airfoil with a chord length (c) of 0.3 m was examined for two Reynolds numbers (Re_c) based on chord length, 10×10^4 and 15×10^4, and three angles of attack (α), 0°, 5° and 10°. All experiments were conducted in a recirculating wind tunnel with a 0.91 × 1.22-m cross-section and a free-stream turbulence intensity level of less than 0.1%.

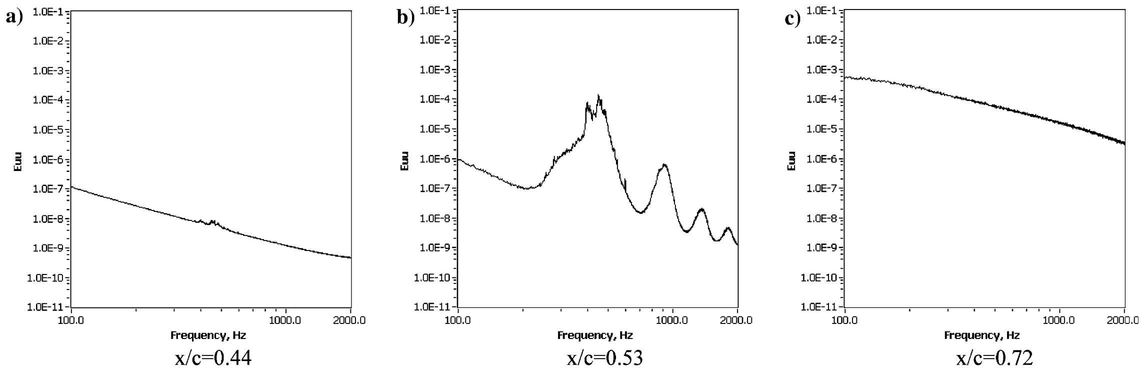
Flow velocity data were acquired with hot-wire anemometry. The maximum hot-wire measurement error was evaluated to be less than 5%. The surface pressure measurements were performed using 65 pressure orifices, with an uncertainty of less than 2%.

3 Results

Detailed surface pressure measurements, not presented here, suggest that laminar boundary layer separation occurs on the upper surface of the airfoil for $Re_c = 15 \times 10^4$ and $Re_c = 10 \times 10^4$ at the angles of attack examined. For $Re_c = 15 \times 10^4$, the boundary layer reattaches to the airfoil surface, forming a separation

S. Yarusevych (✉) · P. E. Sullivan
Department of Mechanical and Industrial Engineering,
University of Toronto, 5 King's College Rd,
Toronto, ON, M5S 3G8, Canada
E-mail: yarus@mie.utoronto.ca
Tel.: +1-416-9786444
Fax: +1-416-9787753
E-mail: sullivan@mie.utoronto.ca
Tel.: +1-416-9783110
Fax: +1-416-9787753

J. G. Kawall
Department of Mechanical and Industrial Engineering,
Ryerson University, 350 Victoria St.,
Toronto, ON, M5B 2K3, Canada
E-mail: gkawall@ryerson.ca
Tel.: +1-416-9795000
Fax: +1-416-9795265



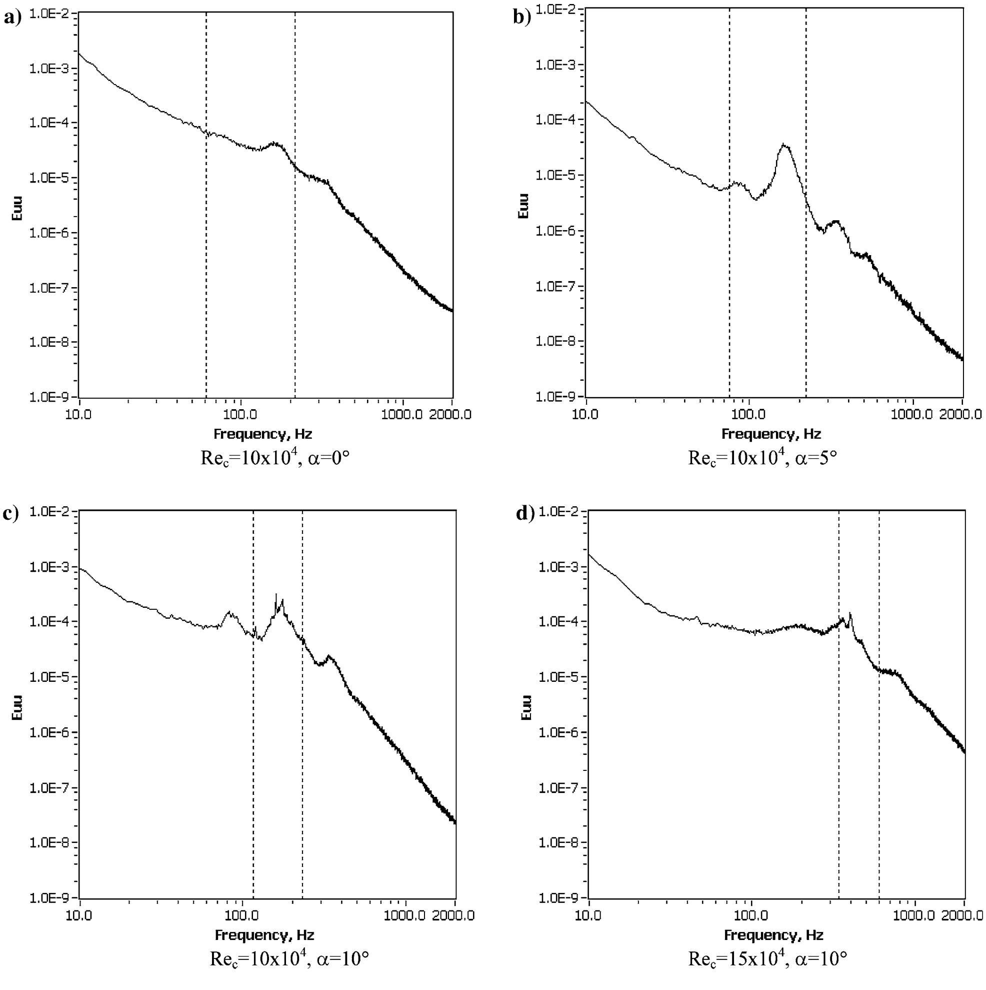
x/c=0.44 x/c=0.53 x/c=0.72

Fig. 1 E_{uu} spectra for $Re_c = 15\times10^4$, $\alpha = 5°$

bubble; however, for $Re_c = 10 \times 10^4$, it fails to reattach and a wider wake is formed.

To gain additional insight into the boundary layer transition process, the spectra of the velocity data obtained in the separated shear layer were examined. The velocity data at each streamwise location (x/c) were acquired at a vertical position that corresponds to the maximum RMS velocity value. The duration of a sampled signal segment was chosen to be sufficiently large to provide a frequency resolution bandwidth of 0.61 Hz. The uncertainty of the spectral analysis was approximately 5%. The presented spectra are normalised by the variance of the streamwise velocity component, so the area under each curve is unity.

Figure 1 depicts the spectra of the streamwise velocity (E_{uu}) for $Re_c = 15 \times 10^4$ at $\alpha = 5°$. Downstream of the separation point at $x/c = 0.44$, a band of unstable Fourier components, sometimes referred to as a wave packet, occurs in an otherwise flat spectrum from 360 Hz to about 500 Hz (Fig. 1a). Further downstream, at $x/c = 0.53$, disturbances in this frequency band are



Re_c=10x10^4, α=0° Re_c=10x10^4, α=5°

Re_c=10x10^4, α=10° Re_c=15x10^4, α=10°

Fig. 2a–d E_{uu} spectra and effective frequency ranges: **a)** $x/c = 0.53$, **b)** $x/c = 0.44$, **c)** $x/c = 0.37$, **d)** $x/c = 0.31$

substantially amplified and the band itself broadens, remaining centred at a fundamental frequency (f_0) of about 420 Hz (Fig. 1b); in addition, harmonics are generated. Rapid transition follows, with a ‘‘classical’’ turbulent spectrum occurring at $x/c = 0.72$ (Fig. 1c). A similar transition mechanism was observed for $Re_c = 10 \times 10^4$, with the amplified disturbances centred at lower fundamental frequencies.

Yarusevych et al. (2003) used external acoustic excitation to improve the performance of a NACA 0025 airfoil in the same experimental facility. The results established that excitation in a certain range of frequencies was efficacious, for a fixed amplitude, with excitation at some optimum frequency being the most efficient.

Figure 2 shows the spectra of the boundary layer velocity data for $Re_c = 10 \times 10^4$ at $\alpha = 0°$, 5° and 10° and for $Re_c = 15 \times 10^4$ at $\alpha = 10°$, with margins of effective frequency ranges from Yarusevych et al. (2003) marked by dashed lines. For $Re_c = 10 \times 10^4$ at $\alpha = 0°$ and 5° (Fig. 2a, b), the effective frequency range includes bands of naturally amplified disturbances centred at the fundamental frequency, f_0, and its first subharmonic, $f_0/2$. As the angle of attack increases to $\alpha = 10°$, the effective frequency range narrows and, for both $Re_c = 10 \times 10^4$ and $Re_c = 15 \times 10^4$ (Fig. 2c, d), it contains only the band of amplified disturbances centred at the fundamental frequency. These results suggest that, at small angles of attack, excitations improve airfoil performance when applied at frequencies close to the fundamental frequency of the naturally amplified disturbances in the separated shear layer and its first subharmonic; whereas, with an increase of the angle of attack, only excitation at frequencies in the band around the fundamental frequency are efficacious. However, for all the cases examined, the optimum excitation frequency approximately matches the fundamental frequency of the amplified disturbances. The only significant deviation of the optimum frequency from the fundamental frequency, about 20%, is found for $Re_c = 10 \times 10^4$ at $\alpha = 0°$. In other instances, the maximum deviation does not exceed 5%. It can, therefore, be concluded that matching the excitation frequency with the frequency of the most amplified disturbance in the separated shear layer is the best method of improving airfoil performance at a given excitation amplitude, Reynolds number and angle of attack.

It is important to be able to predict optimum frequencies for the design of various flow control systems that employ periodic excitation. In this study, initial spatial growth of the disturbances in the separated shear layer was almost exponential, similar to the results of Lang et al. (2004). Therefore, linear stability theory may be used to model the initial stage of transition and to predict optimum excitation parameters.

4 Conclusions

Laminar boundary layer separation occurs on the upper surface of the NACA 0025 airfoil for $Re_c = 15 \times 10^4$ and $Re_c = 10 \times 10^4$ and at angles of attack of $\alpha = 0°$, 5° and 10°. The results establish that the optimum excitation frequency for acoustic boundary layer control matches that of the most amplified disturbance in the separated shear layer for a given Reynolds number and angle of attack. Exciting the boundary layer at that frequency promotes the transition, bringing about earlier boundary layer reattachment. Analysis also indicates that linear stability theory may be used to predict optimum excitation parameters.

Acknowledgements The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for the funding of this work.

References

Lang M, Rist U, Wagner S (2004) Investigations on controlled transition development in a laminar separation bubble by means of LDA and PIV. Exp Fluids 36:43–52

Mueller TJ, DeLaurier JD (2003) Aerodynamics of small vehicles. Annu Rev Fluid Mech 35:89–111

Yarusevych S, Kawall JG, Sullivan PE (2003) Effect of acoustic excitation on airfoil performance at low Reynolds numbers. AIAA J 41:1599–1601

Zaman KBMQ (1992) Effect of acoustic excitation on stalled flows over an airfoil. AIAA J 30:1492–1499