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Experimental Studies on Unsteady Lateral Blowing on a NACA 0012

Chi Wong* and Konstantinos Kontis†
University of Manchester,
Manchester, England M60 1QD, United Kingdom

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I. Introduction

THE initial study of steady lateral blowing was conducted by Dixon in 1969 [1]. The mechanism of this concept is analogous to the flow over slender delta wing platforms, which produces a leading-edge vortex and nonlinear lift curves. Steady lateral blowing might be thought of as providing the sweep effects such as those of the delta wings, for which the effective sweep is a function of the jet momentum. The lateral blowing jet can be described in terms of the chordwise position along the airfoil section, the nozzle height, and the nozzle size.

Dixon et al. [2] and Clarke [3] suggested that the best vertical nozzle position may be a function of the nozzle diameter and that the jet from a nozzle placed too near the airfoil surface may have a deleterious effect on the flow over the airfoil. Wong and Kontis [4] performed a comprehensive study on the steady spanwise blowing on a NACA 0012 airfoil section. The force measurements showed that the lift coefficient increased when the steady lateral blowing was applied, and the most effective blowing location was found to be at $x/c = 0.25$ (x is the chordwise location and c is the airfoil chord), because the lift augmentation ratio $\Delta C_l/C_\mu$ was always above one for all positive angles of attack [ΔC_l is the increment in the lift coefficient due to blowing, and C_μ is the blowing momentum coefficient; the definition of C_μ is shown in Eq. (1)]. However, large momentum was required to generate the lift enhancement on the airfoil and this became a major issue in the effectiveness of blowing. As a consequence, Meyer and Seginer [5] performed some initial tests for generating the same lift increase using lower momentum through pulsed blowing.

One of the main disadvantages of lateral blowing is due to the fact that air for blowing is bled from the compressor stage of the engine. This reduces the amount of air for combustion, hence reducing thrust. Unsteady blowing provides the beneficial effect of reducing the mass-flow requirement from the engine. Another adverse effect of the technology arises from the need to install plumbing, control valves, regulators, oscillators, etc., to supply and control the compressed air from the engine. This adds weight to the aircraft, and a higher lift is required.

$$C_\mu = \frac{\text{thrust}}{qS} = \frac{\dot{m}(U_J)}{q(c)(b)} \tag{1}$$

where $\dot{m}$ is the mass-flow rate of the jet, U_J is the jet velocity, q is the dynamic pressure, and b is the span of the airfoil.

The objectives of the present study are to expand the existing experimental database and to extend the understanding of the effects of unsteady blowing on the aerodynamic performance. The present topic is the subject of ongoing research.

II. Experimental Setup

Measurements were conducted in a low speed blown-down type wind tunnel that has a test section of 458 mm in height, 458 mm in width, and 1750 mm in length. The freestream turbulent intensity of the wind tunnel is less than 0.28%. Measurements were made at a freestream velocity of 12 m/s. A NACA 0012 airfoil model of span 458 mm was mounted horizontally in the test section. The chord of the model, c, was 151 mm. The Reynolds number based on the chord length and freestream velocity was 1.24×10^5. The airfoil was manufactured and polished to a smooth finish. The boundary-layer trips were not employed, thus the tests were performed in a transition-free condition. Unsteady lateral blowing was realized by injecting an unsteady jet in the direction parallel to the span of the airfoil. The blowing-jet nozzle was of a circular cross section with an inside diameter of 4 mm. It passed through the wall of the test section and extended by approximately 4 mm over the span at a height of 1 mm above the surface of the airfoil. The layout of the experiments is shown in Fig. 1. The time-averaged forces and moments were measured at different pulsing frequencies with a three-component external strain gauge balance. A 12-bit data acquisition system with a moderate sampling rate of 512 Hz was used. The load cells only suffer from a nonlinearity error of $\pm 0.03\%$ and hysteresis of $\pm 0.02\%$. The nonrepeatability is $\pm 0.01\%$ and the temperature effect is negligible. Aerodynamic forces were normalized by the freestream dynamic pressure q and airfoil area S. The airfoil chord c was used to normalize the pitching moment. The presented data are corrected for the solid blockage and wake blockage. The estimated overall accuracy for the time-averaged (mean) lift, drag, and pitching measurements is ± 2, ± 2.5, and 2%, respectively.

III. Results and Discussions

Figure 2 shows the variation of the time-averaged (mean) lift coefficient C_l at different angles of attack α for the different jet configurations tested. At 0-deg angle of attack, the mean C_l is -0.05, -0.03, and -0.01 for 8-, 12-, and 16-Hz pulsing blowing jets, respectively. Their values are lower than those corresponding to the no-blowing and steady-blowing cases. C_l increases with increasing frequency of the unsteady jet. This is due to the increase of mass-flow rate (and therefore blowing momentum coefficient) with frequency. The lift curve tends to become more linear when the periodically pulsed jet is used, and it exhibits a smaller gradient than in the steady-blowing and no-blowing cases obtained by Wong and Kontis [4]. Figure 2 shows that the mean lift coefficients are not sensitive to the low-frequency blowing jet at high angles of attack. The maximum lift coefficient is located at 10-deg angle of attack for all cases tested. It is approximately 0.72 for the unsteady configurations, which is significantly less than 0.80 and 1.21 for the no-blowing and steady-

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*Research Student, School of Mechanical, Aerospace and Civil Engineering. Student Member AIAA.

†Senior Lecturer, School of Mechanical, Aerospace and Civil Engineering. Member AIAA.

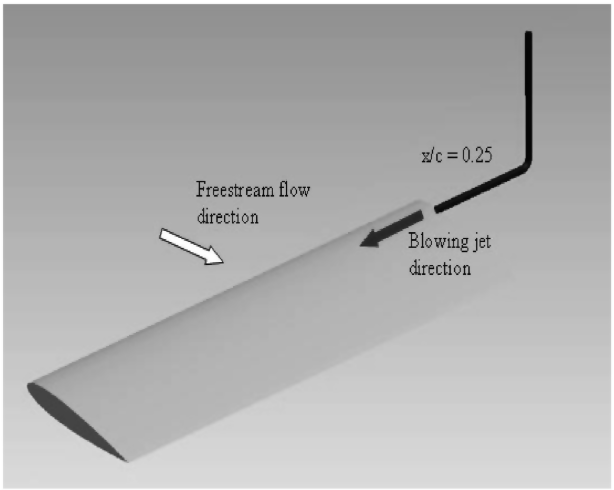

Fig. 1 Illustration of the spanwise blowing at $x/c = 0.25$.

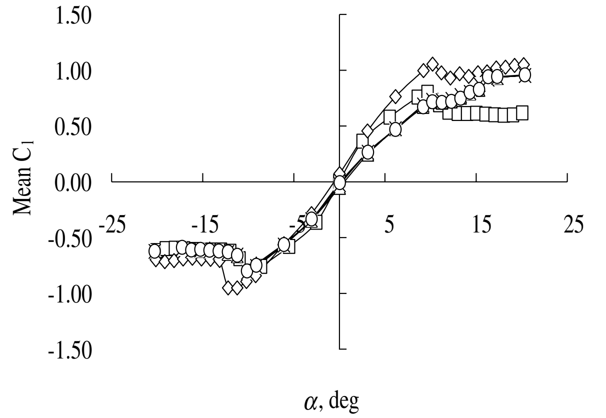

Fig. 2 Comparison of mean lift coefficients; □ no-blowing, ◇ steady blowing, △ 8 Hz, × 12 Hz, and ○ 16 Hz.

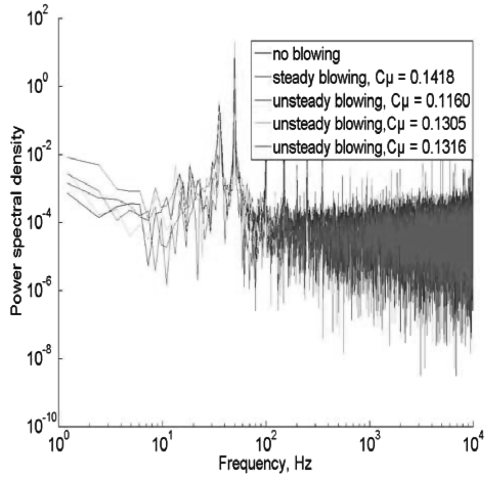

Fig. 3 Power spectral density for different configurations at a 10-deg angle of attack.

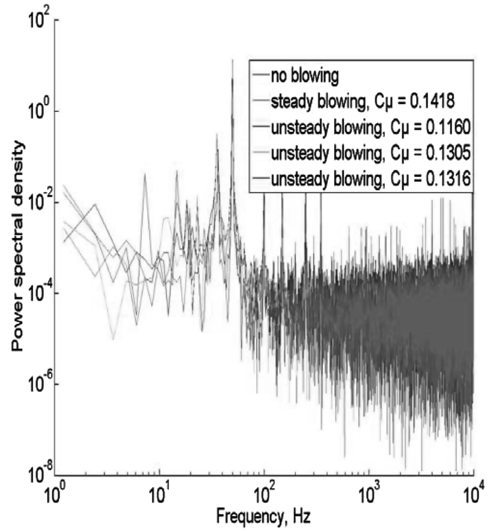

Fig. 4 Power spectral density for different configurations at a 20-deg angle of attack.

blowing cases, respectively. At the poststall angles of attack, the mean lift coefficient increases rapidly and the rate of increase is highly dependent on the frequency of the blowing jet.

Because it is difficult to judge the effectiveness of the periodically pulsed jet from Fig. 2, the spectrum analysis of lift was also performed at 10- and 20-deg angles of attack. The results were processed with the MATLAB program and no digital filters were used. Figure 3 shows the power spectral density (PSD) of the lift component at a 10-deg angle of attack for the different configurations tested. Two distinct peaks can be identified at approximately 38 and 50 Hz. The frequency of 50 Hz is generated from the force balance and it is the main frequency for all electronic applications. The peak at 38 Hz is thought to be the natural frequency of the freestream flow when the pulsed jet is used. A small change in the power spectral density is observed below 10 Hz. It also indicates that the periodically pulsed jet has only a small effect on the flowfield on the suction surface of the airfoil, and it does not induce any influence at high frequencies. It is conjectured that the reduction of lift, which was observed in Fig. 2, was due to the change in the boundary-layer properties caused by the unsteady jet momentum.

Figure 4 shows the PSD of the lift component at a 20-deg angle of attack for the different configurations. The effect of the periodically pulsed jet becomes more apparent and more distinct peaks can be identified. It shows that the pulsed blowing generates a similar magnitude of PSD as the no-blowing case within the low-frequency range (from 1 to 10 Hz). However, the magnitude of PSD for the pulsed blowing is less than the steady-blowing case within the same frequency range. Furthermore, two peaks can be identified for the 8-Hz blowing jet. These peaks are found at 8 and 16 Hz, which are the first and second harmonics of the periodically pulsed jet. This indicates that the airfoil lift produces a frequency response corresponding to the frequency of the blowing jet, and the frequency of the blowing jet becomes a dominant factor to lift production and airfoil performance at high angles of attack. Two peaks can be identified for the 12-Hz blowing jet. These peaks are 12 and 24 Hz, which are the first and second harmonic of the periodically pulsed jet. However, their magnitudes are lower than those with the 8-Hz blowing jet. Therefore, the effect of the pulsed jet on the lift production is diminished as the frequency increases. Finally, a single peak can barely be identified for the 16-Hz blowing jet, and its magnitude is much smaller than the second harmonic of the 8-Hz blowing jet. The magnitude of PSD is unchanged at a high-frequency range (above 100 Hz) for all periodically pulsed jet cases. It is concluded that lift is only sensitive to the lower part of the spectrum, and lift production at high angles of attack is also strongly dependent on both the frequency of the jet and the blowing momentum coefficient.

Figure 5 shows the variation of the time-averaged (mean) drag coefficient C_d at different angles of attack for different blowing conditions. The drag coefficient at a 0-deg angle of attack is 0.05 for all pulsed jet conditions. This is probably due to the induced unsteadiness of the flow on the suction surface, which causes the increase of the skin friction drag. The minimum drag coefficient occurs at a 3-deg angle of attack for all pulsed jet cases, and it is higher than in the steady-blowing case. With increasing angle of

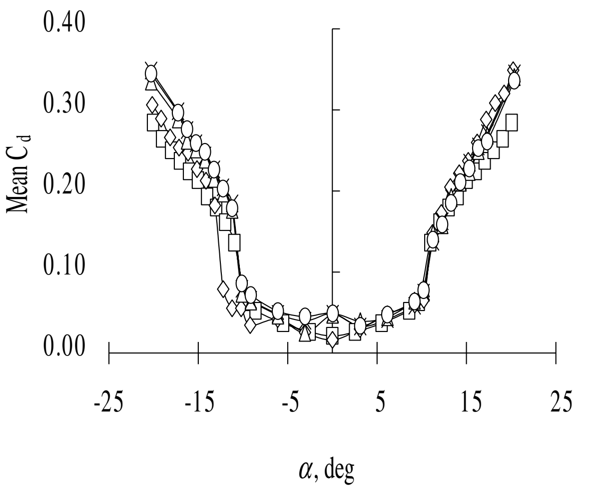

Fig. 5 Comparison of mean drag coefficients; □ no-blowing, ◇ steady blowing, △ 8 Hz, × 12 Hz, and ○ 16 Hz.

attack, the drag increases at approximately the same rate for all pulsed jet cases and very little variation is observed. The drag coefficient increases abruptly at a 11-deg angle of attack, and it is due to the stalling of the airfoil. The drag curves for the pulsed jet cases lie between the curves for the steady and the no-blowing cases. This indicates that the flow pattern over the suction surface is altered by the presence of the periodically pulsed jet. The increase of drag is less for the pulsed jet cases at high angles of attack. Therefore, it is suggested that there is a potential benefit to be gained at high angles of attack when a periodically pulsed jet is applied. It should also be pointed out that some of the drag associated with blowing is contributed from the projection of the nozzle to the streamwise flow.

Figure 6 shows the airfoil performance C_l/C_d for different blowing configurations. The periodically pulsed jet induces a small negative lift at zero angle of attack, thus the C_l/C_d ratio is less than with the steady and no-blowing cases. The C_l/C_d ratio at 6-deg angle of attack is decreased when the 16-Hz blowing jet was used. The C_l/C_d ratio between the 6- and 9-deg angles of attack for the 12-Hz blowing jet is higher than with the value for the 16-Hz blowing jet case. This is closely matched with the cases in which the steady jet was applied at $x/c = 0.25$. This result is probably due to the jet-induced instabilities on the suction surface of the airfoil. It is conjectured that these instabilities are fed into the boundary layer of the airfoil, forcing the formation of a turbulent boundary layer. Further investigations are necessary to confirm this hypothesis. The maximum C_l/C_d ratio occurs at a 9-deg angle of attack when the periodically pulsed blowing is used. The maximum C_l/C_d ratio is 10.79, 11.82, and 10.57 for the 8-, 12-, and 16-Hz blowing jets, respectively. It becomes clear that the frequency of the blowing jet has a direct effect that contributes to the overall airfoil performance, rather than the blowing momentum coefficient only. For the poststall condition, the C_l/C_d ratio is always slightly smaller than the value for the steady jet case, but it is higher than the value for the no-blowing case. This indicates that the airfoil performance has improved with the periodically pulsed blowing. Though the periodically pulsed jet is found to be less effective than both the steady-blowing and no-blowing cases at low angles of attack, it should be emphasized that the periodically pulsed blowing provides nearly the same lift increment as the steady-blowing case at high angles of attack.

Although the airfoil is symmetric, the lift and drag curves are asymmetric (as shown in Figs. 2 and 5), due to the change of the "effective" curvature of the airfoil caused by the unsteady lateral blowing on top of the model. Therefore, the airfoil performance is also asymmetric.

Figure 7 shows the variation of the pitching moment coefficient C_m for different configurations. The unsteady pulsed jet induces a positive pitching moment at all positive angles of attack. This indicates that the airfoil tends to produce a nose-up motion with increasing angle of attack. This occurrence is probably due to the

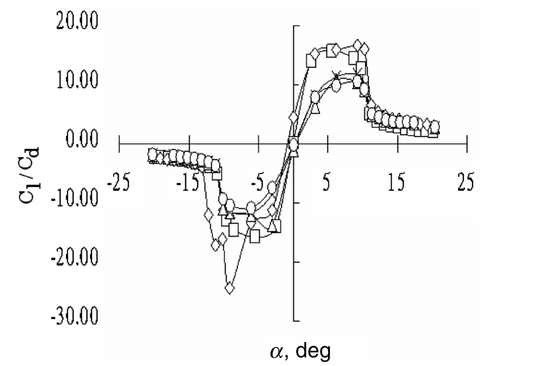

Fig. 6 Comparison of aerodynamic performance; □ no-blowing, ◇ steady blowing, △ 8 Hz, × 12 Hz, and ○ 16 Hz.

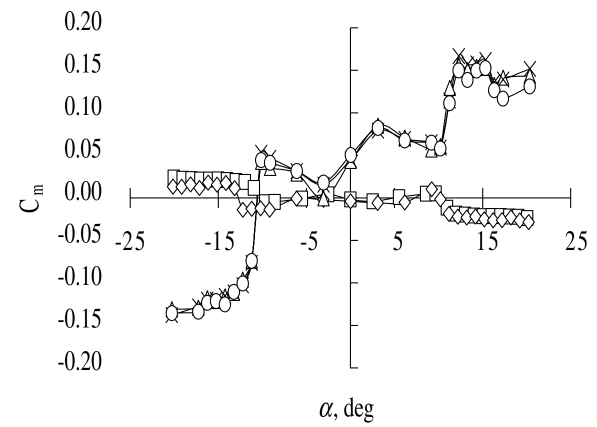

Fig. 7 Comparison of pitching moment coefficient; □ no-blowing, ◇ steady blowing, △ 8 Hz, × 12 Hz, and ○ 16 Hz.

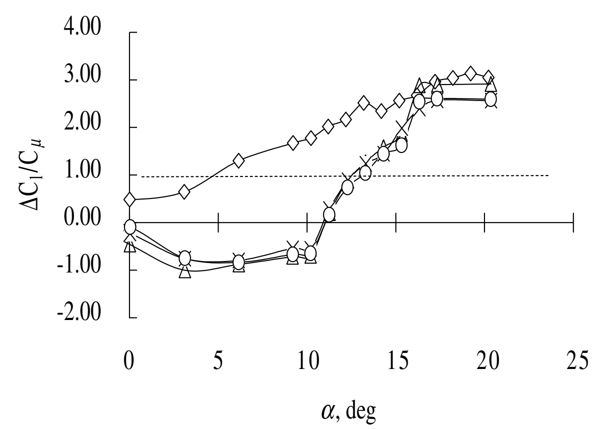

Fig. 8 Comparison of lifting efficiency; □ no-blowing, ◇ steady blowing, △ 8 Hz, × 12 Hz, and ○ 16 Hz.

effect of unsteadiness of the pulsed jet, and it exhibits a dependence on frequency.

The effectiveness of the periodically pulsed jet relative to continuous steady blowing is examined by comparing the lift augmentation ratio $\Delta C_l/C_\mu$. Figure 8 shows that the augmentation ratio becomes negative from 0- to 11-deg angles of attack, such that less lift is produced when the periodically pulsed jet is used. At a 13-deg angle of attack, $\Delta C_l/C_\mu$ becomes greater than one for the periodically pulsed blowing cases. Though the results do not provide any information about the response of the lift augmentation ratio due to the change of frequency of the pulsed jet, it shows that $\Delta C_l/C_\mu$ increases continuously with increasing angle of attack and it becomes similar in value to the steady-blowing case at a 20-deg angle of attack.

IV. Conclusions

When the pulsed jet was applied at $x/c = 0.25$, the lift curve tended to become a linear function and it had a smaller gradient than in the steady-blowing case. This was probably due to the reduction of the effective curvature of the model caused by the unsteady-blowing jet on the suction surface of the model. The lift at moderate angles of attack was insensitive to the different frequencies of the pulsed jet. The effect of frequency of the blowing jet was more pronounced at high angles of attack (typically above 15 deg) and the lift coefficient increased rapidly. Spectral analysis of the lift component acting on the airfoil was performed. The results indicated that the lift component responded to the frequency of the pulsed jet at a 20-deg angle of attack. Therefore, the frequency of the blowing jet became a dominant factor to lift production and airfoil performance at high angles of attack. The unsteadiness of the flow on the suction surface of the airfoil at high angles of attack was governed by the frequency of the blowing jet. The drag production in the pulsed jet cases was lower than the value in the steady-blowing case, but it was slightly higher than the value in the no-blowing case. The increase of drag at moderate angles of attack was probably due to the increase of skin friction drag caused by the presence of the unsteady jet. The maximum C_l/C_d ratio for the pulsed blowing cases was found to be lower than that of the steady-blowing case. Therefore, the airfoil performance was not improved. Further research is currently under way to examine the boundary-layer characteristics and induced flow interactions on the suction surface of the airfoil using time-dependent measurement techniques and therefore to identify the reasons for the detrimental effect on performance.

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