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Technical Notes

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Effect of Acoustic Excitation on Airfoil Performance at Low Reynolds Numbers

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Introduction

AIRFOIL performance at low Reynolds numbers has been of interest in a wide range of applications including the design of unmanned air vehicles and wind turbines. Several investigators have studied airfoil performance in the low Reynolds number region, for example, Ref. 1. Findings of the investigations show that serious aerodynamic problems occur below Reynolds number of about 2×10^5. Specifically, the laminar boundary layer on the upper surface of the airfoil is subjected to an adverse pressure gradient, even at low angles of attack. This often results in either laminar boundary-layer separation and the formation of a large wake or the formation of a laminar separation bubble on the airfoil surface. Both phenomena have a detrimental effect on airfoil lift and drag. Therefore, it is of interest to improve airfoil performance by introducing a flow control mechanism. One method of doing this is exciting the boundary layer with an acoustic source. Several studies have showed that excitation applied at a suitable frequency and amplitude reduces the separation region and improves airfoil characteristics.[2–4] It has been concluded[3,4] that the effect and the effective frequency range of the excitation, that is, the range of frequencies producing improvement of the airfoil characteristics, strongly depend on the excitation amplitude. However, the various experimental attempts to predict optimum values of the excitation parameters and to explain the attendant flow control mechanism have resulted in a wide range of sometimes contradictory conclusions.[4]

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The present work examines the effect of external acoustic excitation on airfoil performance and wake structure.

Experimental Setup

Experiments were performed in a low-turbulence recirculating wind tunnel with a 0.9×1.22 m test section and a freestream turbulence intensity level less than 0.05%. The performance of a symmetrical NACA 0025 airfoil with a chord length c of 0.3 m and a span of 0.88 m was examined for three chord Reynolds numbers Re_c and three angles of attack α. A 250-W loudspeaker mounted on the test section floor, under the leading edge of the airfoil, provided the acoustic excitation.

Airfoil wake velocity data were obtained with Dantec constant temperature anemometers. A normal hot-wire probe and a cross-wire probe were used separately to traverse vertical planes downstream of the airfoil. For accurate detection of vortex-shedding frequencies, the probe position was adjusted with Reynolds number and angle of attack. Spectral analysis of the freestream velocity signals established there was no periodicity associated with the approaching flow. The frequency resolution of the spectral analysis was 0.6 Hz. Nylon tufts were used to visualize boundary-layer behavior.

Experimental Results

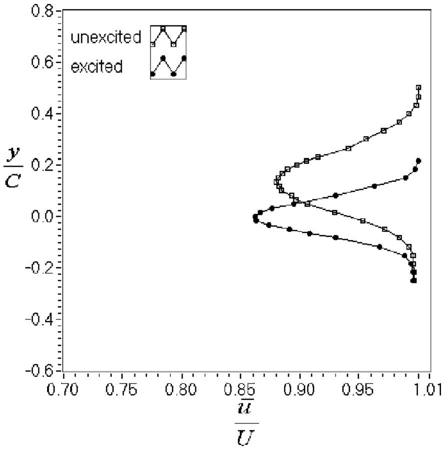
The experiments were performed for Reynolds numbers Re_c of 150×10^3, 100×10^3, and 57×10^3 and angles of attack α of 10, 5, and 0 deg. Boundary-layer separation occurred over a large region (~50%) on the upper surface of the airfoil at these angles of attack for $Re_c = 57 \times 10^3$ and $Re_c = 100 \times 10^3$, but only over a small region at $\alpha = 10$ deg for $Re_c = 150 \times 10^3$. Because of boundary-layer separation, much wider wakes, with substantially higher turbulence intensities in the core region, were formed at all angles of attack for $Re_c = 57 \times 10^3$ and $Re_c = 100 \times 10^3$ compared with those at similar angles of attack for $Re_c = 150 \times 10^3$.

It was found that acoustic excitation introduced with sufficient amplitude and at particular frequencies, which form an effective-frequency range, reduces or suppresses the separation region on the surface of the airfoil. As the amplitude of the excitation decreased, this range narrowed, with boundary-layer reattachment finally occurring only at some "optimum" excitation frequency. The results summarized in Table 1 show the same trends as those obtained by others, that is, an increase of the effective-frequency range with an increase of Reynolds number[4] and a decrease of the angle of attack.[2] The experimental analysis of Zaman and McKinzie[4] also suggest that, for $\alpha \leq 6.5$ deg, the Strouhal number (fc/U) divided by the square root of the Reynolds number, $Sr_c/Re_c^{1/2}$, ranges from 0.02 to 0.03 for the optimum excitation frequency. The values of this parameter obtained in the present work are within the suggested range, except the value at $\alpha = 5$ deg for $Re_c = 57 \times 10^3$ (which is 10% greater than the maximum value suggested in Ref. 4). Note that only results for acoustic excitation applied at optimum frequencies are considered in what follows.

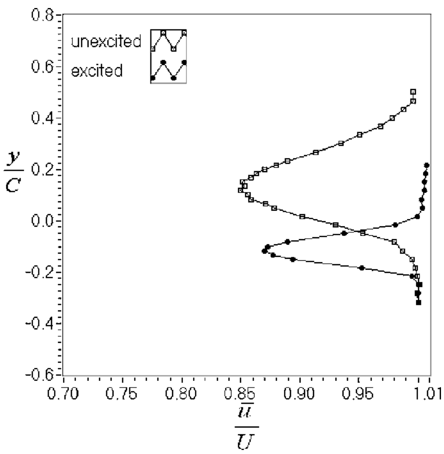
Figure 1 shows the effect of acoustic excitation on mean-velocity wake profiles for $Re_c = 100 \times 10^3$ at $x/c = 2$. The observed asymmetry of the unexcited wake profile at $\alpha = 0$ deg (Fig. 1a) is due to a bigger separation region on the upper surface of the airfoil compared to that on the lower surface. This phenomenon might be a result of high sensitivity of the low Reynolds number flows to the test section environment and has been noted by others.[5] It is clear from Fig. 1

Table 1 Effective acoustic excitation frequencies

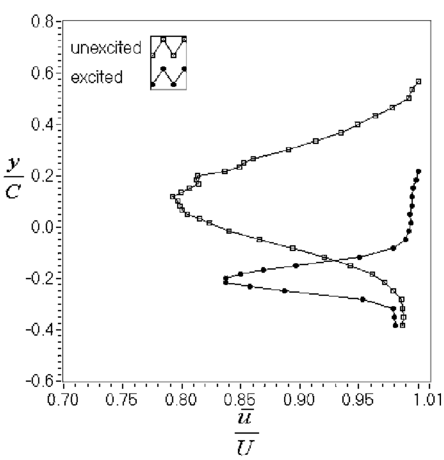
	$\alpha = 0$ deg			$\alpha = 5$ deg			$\alpha = 10$ deg		
Re_c	Effective-frequency range, Hz	Optimum frequency, Hz	$\frac{Sr_c}{Re_c^{1/2}}$	Effective-frequency range, Hz	Optimum frequency, Hz	$\frac{Sr_c}{Re_c^{1/2}}$	Effective-frequency range, Hz	Optimum frequency, Hz	$\frac{Sr_c}{Re_c^{1/2}}$
57×10^3	40–88	65	0.029	70–80	75	0.033	75–85	80	0.036
100×10^3	45–205	117	0.022	75–220	162	0.030	115–230	169	0.031
150×10^3	——	——	——	——	——	——	370–600	450	0.045



a) $\alpha = 0$ deg

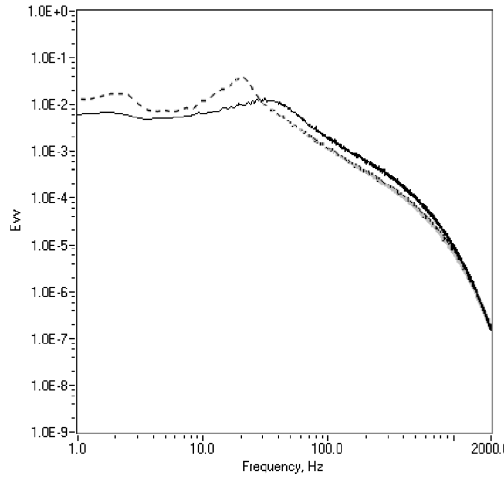


b) $\alpha = 5$ deg

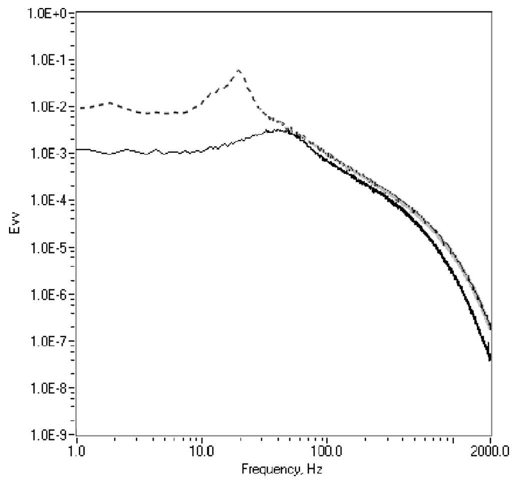


c) $\alpha = 10$ deg

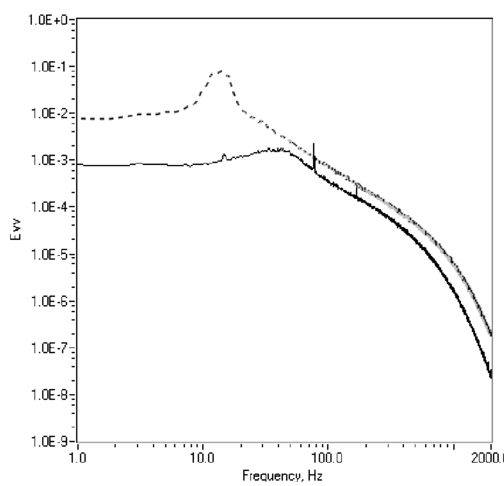
Fig. 1 Mean profiles with and without excitation for $Re_c = 100 \times 10^3$ at $x/c = 2$.



a) $\alpha = 0$ deg



b) $\alpha = 5$ deg



c) $\alpha = 10$ deg

Fig. 2 E_{vv} spectra with and without excitation for $Re_c = 100 \times 10^3$ at $x/c = 3$: - - - -, unexcited flow and ——, excited.

Table 2 Normalized airfoil drag coefficients

	C_d/C_{d0}^{a}		
Re_c	$\alpha = 0$ deg	$\alpha = 5$ deg	$\alpha = 10$ deg
57×10^3	0.6155	0.8534	0.9389
100×10^3	0.7054	0.3870	0.2475
150×10^3	——	——	0.7596

[a]Drag coefficient without excitation/drag coefficient with excitation.

that acoustic excitation significantly narrows the wake at all three angles of attack. Notice that once the separation on both sides of the airfoil has been suppressed at $\alpha = 0$ deg (Fig. 1a), the mean profile is symmetric as expected. In addition, the wake shifts down, following the incline of the trailing edge at $\alpha = 5$ and $\alpha = 10$ deg (Figs. 1b and 1c), similar to airfoil wakes at high Reynolds numbers when the Kutta condition is satisfied.

A quantitative analysis of the effect of acoustic excitation on airfoil performance is based on the drag coefficient results (Table 2), obtained by integration of the mean-wake profiles. The most significant reduction of the drag coefficient is achieved for $Re_c = 100 \times 10^3$, with the drag coefficient reduced by 75% at $\alpha = 10$ deg. It is also obvious that a greater decrease of the drag coefficient is achieved for $Re_c = 100 \times 10^3$ than for $Re_c = 57 \times 10^3$, except for $Re_c = 57 \times 10^3$ at $\alpha = 0$ deg. Indeed, separation regions, comparable in size for these two Reynolds numbers at corresponding angles of attack, were only reduced for $Re_c = 57 \times 10^3$, whereas they were suppressed for $Re_c = 100 \times 10^3$ with the same power input. It can be concluded that higher amplitude excitations are needed to influence the airfoil performance at lower Reynolds numbers. Note that decrease of the drag coefficient for $Re_c = 100 \times 10^3$ becomes more pronounced as the angle of attack increases (Table 2). This trend is due to suppression of the separation region, which increases as angle of attack increases. The improvement of the airfoil performance for $Re_c = 150 \times 10^3$ is less significant than it is for the $Re_c = 100 \times 10^3$. Nevertheless, a separation region on the upper surface of the airfoil was suppressed by acoustic excitation, and a 24% decrease of the drag coefficient resulted.

To assess the effect of acoustic excitation on coherent structures in the airfoil wake, transverse velocity component spectra E_{vv} are presented. Figure 2 shows the E_{vv} spectra for $Re_c = 100 \times 10^3$ at $x/c = 3$. The peaks in the spectra associated with the unexcited flow are clear evidence of vortex shedding in the airfoil wake at all angles of attack. Peaks corresponding to 0-, 5-, and 10-deg angles of attack centred at 20, 20, and 14 Hz are strongly attenuated, broadened and shifted to 30, 40, and 40 Hz, respectively, suggesting that vortex coherency and length scale are decreased by acoustic excitation. It can also be inferred from comparison of the results in Fig. 2 and Table 1 that the optimum excitation frequency does not match the vortex-shedding frequency but is an order of magnitude greater. It is speculated that the optimum frequencies found in this investigation match the separated shear layer instability frequencies, agreeing with the results of Refs. 2 and 4. Note that the effect of the acoustic excitation on the vortex shedding for this Reynolds number is similar to the effect on the drag coefficient (Table 2) because a more significant diminishment of the peaks in the spectra is achieved for higher angles of attack.

Conclusions

External acoustic excitation at particular frequencies and suitable amplitudes can substantially reduce or suppress the separation region of an airfoil so that an increase in lift and/or a decrease in drag result. The effect of the excitation strongly depends on the excitation frequency and amplitude. In particular, the effective-frequency range decreases with a decrease of the excitation amplitude. For a constant amplitude excitation, this range narrows with a decrease of the Reynolds number or increase of the angle of attack. It is speculated that the optimum frequencies found in this investigation match separated shear-layer instability frequencies, in agreement with Refs. 2 and 4. The results also suggest that higher amplitude excitations are needed to influence the airfoil performance at lower Reynolds numbers.

The acoustic excitation alters wake structure, decreasing the vortex length scale and the coherency of the vortices. Also, the magnitude of the acoustic excitation effect on the wake structure correlates with the extent of the improvement in the airfoil performance.

Acknowledgments

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References

[1]Lissaman, P. B. S., "Low Reynolds Number Airfoils," *Annual Review of Fluid Mechanics*, Vol. 15, 1983, pp. 223–239.

[2]Hsiao, F. B., Jih, J. J., and Shyu, R. N., "The Effect of Acoustics on Flow Passing a High-AOA Airfoil," *Journal of Sound and Vibration*, Vol. 199, No. 2, 1997, pp. 177–178.

[3]Zaman, K. B. M. Q., "Effect of Acoustic Excitation on Stalled Flows over an Airfoil," *AIAA Journal*, Vol. 30, No. 6, 1992, pp. 1492–1499.

[4]Zaman, K. B. M. Q., and McKinzie, D. J., "Control of Laminar Separation over Airfoils by Acoustic Excitation," *AIAA Journal*, Vol. 29, No. 7, 1991, pp. 1075–1083.

[5]Mallon, K. J., Levinski, O. P., and Brown, K. C., "Experimental Investigation of the Unsteady Aerodynamics of a Symmetric Aerofoil at Low Reynolds Numbers," *Proceedings of Second Pacific International Conference on Aerospace Science and Technology/Sixth Australian Aeronautical Conference*, Vol. 1, Institution of Engineers Australia/Royal Aeronautical Society, Melbourne, Victoria, Australia, 1995, pp. 475–484.

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Robust-Optimal Design of a Lightweight Space Structure Using a Genetic Algorithm

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I. Introduction

WHEN using a "perfect" computer model of a structure to optimize its dynamic (vibration) performance, the results rely on the exactness of the model and can in practice be very sensitive to small changes in design variables. This is especially the case in the mid- and high-frequency regions where modal overlap occurs. To assess this, the multidimensional gradient of the search space at the current design point can be approximated, or changes in the performance of the structure caused by "local" variations in design variables can be calculated. Both of these normally carry a high computational expense, especially for high-dimensional problems.

Here the optimization of a structure using genetic algorithms (GA)[1] is described, for which the robustness of the structure's performance is also considered. One type of GA used efficient methods

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