NUMERICAL SIMULATION OF ACTIVE FLOW CONTROL BASED ON STREAMWISE VORTICES FOR A BLUNT TRAILING EDGE AIRFOIL

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Abstract. Numerical simulations of the flow around a blunt trailing edge airfoil are carried out to identify the three dimensional structure of wake vorticity. Based on the results of the simulations, an active flow control mechanism is proposed to enhance the wake streamwise vorticity. The flow control mechanism involves injection of small amounts of secondary flow at the base of the airfoil, with a spanwise spacing which is proportional to the natural spacing of streamwise vortices. As a result of amplification of streamwise vorticity, the formation region is elongated and the von Kármán vortex street is disorganized. Amplitude of the fluctuating aerodynamic forces is also decreased considerably. The proposed flow control mechanism provides a basis for development of a more efficient reactive control system which would involve sensing of flow parameters correlated with streamwise vorticity, to activate individual injectors on a selective basis.
1 INTRODUCTION

Previous studies have shown that three-dimensional features of the wake behind blunt trailing edge objects with different forebody geometries can be manipulated to disorganize and attenuate strength of von Kármán vortices, and thereby to reduce fluctuating lift and drag forces. Bearman and Tombazis (Ref. [1] and Ref. [2]) achieved a 34% decrease in base drag by using a passive control technique which involved spanwise periodical protrusions at the trailing edge of blunt trailing edge flat plate profiles. They related the drag reduction associated with mitigation of vortex shedding to the development of three dimensional structures in the shear layer.

Darekar and Sherwin (Ref. [3]) numerically explored the effects of the amplitude and the spanwise periodicity of the sinusoidal protrusions on aerodynamic forces of a square cylinder with wavy leading and trailing edges. They demonstrated that when the wavelength of the spanwise protrusions is close to the natural spanwise spacing of pairs of counter-rotating streamwise vortices ($\lambda_z$), a considerable reduction in lift and drag fluctuations, which is accompanied by a significant reduction of Strouhal number, can be achieved, even when protrusions have a very small amplitude. Their numerical simulations, however, were limited to low Reynolds numbers in the order of $10^6$.

The three dimensional intermediate wake flow topology at a relatively high Reynolds number of $10^6$ has been studied experimentally for a square cylinder by Dobre and Hangan in Ref. [4]. Based on their findings, Dobre, Hangan, and Vickery implemented a flow control scheme based on spanwise sinusoidal perturbations in Ref. [5], and showed that the best control efficiency in terms of vortex shedding mitigation is achieved when the near wake is excited by sinusoidal perturbations spaced at a wavelength corresponding to the statistical spanwise location of streamwise vortex pairs. The spacing ($\lambda_z$) was found to be $2.4d$ in their case, in which $d$ is thickness of the trailing edge. An almost similar value of $\lambda_z = 2.2d$ was reported by Hangan et al. in Ref. [6], for the intermediate wake of a circular cylinder at $Re = 6.7 \times 10^3$. El-Gammal and Hangan (Ref. [7]) extended these topological findings to blunt and divergent trailing edge airfoils, and achieved a significant attenuation of von Kármán vortices using sinusoidal protrusions with a wavelength equal to $\lambda_z = 2.4d$, at $Re(d) = 1.3 \times 10^4$.

The spacing of perturbations is fixed in all passive flow control schemes mentioned above. However, the spacing of streamwise vortices is governed by the secondary wake instability modes. As different combinations of these modes arise at different Reynolds numbers (Ref. [8]), one should not expect the spacing to remain constant over a broad range of Reynolds numbers. As a result, any passive control scheme would be efficient only at the single Reynolds number and inlet conditions for which it is designed.

This fact is the principal motivation for the present study, which aims at developing a flow control system able to amplify streamwise vortices with variable spacing. When combined with a mechanism to sense the instantaneous location of streamwise vortices, such a flow control mechanism would be able to achieve the objective of suppressing the vortex shedding more effectively over a broader range of Reynolds numbers and flow conditions.

The baseline geometry over which the flow control mechanism is simulated is similar to the one used by Tombazis and Bearman in Ref. [9]. It is a flat plate airfoil consisting of an elliptical nose, followed by a rectangular section, as shown in Fig. (1). This geometric configuration is popular in the wake control literature, because it provides the desired upstream boundary layer velocity profile at the trailing edge, without the uncontrollable effects of forced separation-reattachment associated with sharp leading edge corners. The geometric model has a span of 457.2mm, a chord of 321.5mm, a semi-major axis length of 65.5mm for
the elliptical section, and a total thickness of 29.4mm. These dimensions are selected in accordance with the requirements of future wind tunnel tests, and to facilitate comparison of the results with the experimental results reported by Doddipatla et al. in Ref. [10].

![Figure 1: Geometry and dimensions of the flat plate airfoil](image)

2 THE BASE CASE (NO-CONTROL)

The following section describes details and results of numerical simulation of flow around the blunt trailing edge airfoil introduced in the previous section. The results, which include wake vorticity structure and the resulting aerodynamic forces, provide a basis for determining of the flow control mechanism requirements, and to evaluate its efficiency.

2.1 The numerical model

The solution domain is defined as a hexahedral volume surrounding the airfoil. The domain extends 5 chord lengths behind, 2 chord lengths in front, and 2 chord lengths from the upper and lower surfaces of the airfoil. The distances between the solid surfaces of the airfoil and the domain boundaries are selected on a trial and error basis, so that the perturbations caused by the airfoil diminish to a level that would not cause any numerical error or inconsistency when they reach the boundaries. Fig. (2) shows a schematic of the solution domain and its boundaries.

A combination of structured, boundary layer-type grid, and unstructured grid is used to in the solution domain. The region surrounding the solid walls of the airfoil, as well as the region covering the near wake (3d downstream from the base of the airfoil) is discretized using a structured grid of hexahedral cells, which are refined towards the solid surfaces. The remaining portion of the solution domain, which encompasses the previously mentioned region, is discretized using an unstructured grid of tetrahedral cells. The grid size has been previously increased in steps of +25% until grid in dependence in terms of surface distribution of pressure coefficient $C_p$ is achieved. A close up of the final hybrid grid, which has a total of $1.05 \times 10^6$ cells, is shown in Fig. (3).

A segregated implicit scheme based on the SIMPLE algorithm has been used for solution of the governing equations in space. Temporal discretization is carried out using a time step size of $5 \times 10^{-5}$ sec. This time step is approximately $\sqrt{2/50} T_s$, where $T_s$ is the predicted shedding period of von Kármán vortices. Details of the numerical solution procedure can be found in Ref. [11].
2.2 Wake characteristics

Results of numerical simulations at a freestream velocity of $U_\infty = 10 \text{m/s}$, which is equivalent to a Reynolds number of $\text{Re}_d = 2 \times 10^4$ based on the thickness of the airfoil or $\text{Re}_c = 2.2 \times 10^5$ based on the chord, are analyzed to study the three-dimensional vorticity structure in the wake.

Results indicate formation of a von Kármán vortex street in the wake of the airfoil, as shown in fig. (4). The average shedding frequency of the primary, spanwise vortices is $f_z = 77 \text{Hz}$, which results in a Strouhal number of $St = 0.23$. This value of Strouhal number is in agreement with the one found by Bearman and Tombazis (Ref. [1]) for the same geometry at Reynolds numbers of the same order of magnitude as the one analyzed herein.
In order to analyze the three-dimensional structure of the counter-rotating streamwise vortices which accompany with the primary spanwise vortices, the spatial and temporal variations of the streamwise vorticity are studied along a series of spanwise lines at 4 downstream locations of $x/d = 0, 0.25, 0.5, 1.0$, where $x/d = 0$ corresponds to the upper trailing edge, as shown in Fig. (5).

![Figure 4: Vorticity contours on the mid-plane of the solution domain, showing formation of the von Kármán vortex street](image)

![Figure 5: Location of spanwise lines along which spatial and temporal variations of vorticity is studied](image)

Fig. (6) shows spatial and temporal variations of the streamwise component of vorticity ($\omega_x$) along line 4, which is located at $x/d = 1.0, y/d = 0.5$. Emergence and evolution of streamwise vorticity, which accompanies the periodic shedding of spanwise vortices, can be observed clearly in this figure. It should be noted that the horizontal axis, which represents time, can be replaced with the streamwise distance based on Taylor’s hypothesis (Ref. [12]), which makes it possible to use the following relation to convert time to streamwise distance:

$$\Delta x = -U_c \Delta t$$ \hspace{1cm} (1)

In the above-mentioned relation $U_c$ is the convective velocity of the spanwise vortices, which is found to be $U_c = 0.89 U_\infty = 8.9 \text{ m/s}$ for the present simulation. Based on this rela-
tion, the horizontal span of Fig.(6) can be assumed to represent a streamwise distance of $166d$, approximately.

Spatial and temporal variations of streamwise vorticity ($\omega_x$) for the other lines shown in Fig.(5) show a behavior similar to that of line 4, with decreasing intensity for locations closer to the base of the airfoil.

Fig.(6) also indicates that the pairs of counter-rotating streamwise vortices occur with a periodic nature across the span. In order to determine the spanwise spacing of the streamwise vortices, a phase averaged plot of streamwise vorticity across the span at $x/d = 1$ is presented in Fig. (7). The average spanwise spacing of streamwise vortex pairs in Fig. (7) is $\lambda_z / d = 2.14$. This spanwise spacing, which is close to the experimental values reported in Refs. [4], [5], and [6], will be used to configure the flow control mechanism in the following section.

Figure 6: spatial and temporal variations of the streamwise component of streamwise vorticity ($\omega_x$) along line 4 ($x/d = 1$)

Figure 7: Phase averaged plot of streamwise vorticity across the span on line 4 ($x/d = 1$)
2.3 Aerodynamic forces

Time histories of the airfoil’s lift and drag are shown in Fig. (8). The effect of vortex shedding can be observed as periodic variations of aerodynamic forces. The period of fluctuations of drag is $2f_s$, since base drag is affected by base pressure variations caused by shedding of vortices from either side of the trailing edge, which occurs twice during each shedding period (see also Ref. [7]).

The long period variations of lift and drag amplitudes can be attributed to the low-frequency modulations of the von Kármán vortex street, which are caused by the three dimensionality of vortex shedding, appearing as streamwise and vertical vorticity components. This phenomenon, which has been investigated in detail by Wu et al. in Ref.[13], occurs with a period which is 10 to 20 times larger than the primary vortex shedding period $T_s$. A comparison of the force history diagrams of Fig.(8) with spatial and temporal variations of streamwise vorticity shown in Fig.(6) indicates that the amplitude of fluctuating forces resulting from the primary spanwise vortices is smaller when streamwise vortices are stronger (around $t = 0.4s$). This observation is in accordance with previous findings described in section 1, which suggest that amplification of streamwise vortices can lead to attenuation of the primary spanwise vortices.

![Figure 8: Time histories of the airfoil’s lift and drag](image)

3 FLOW CONTROL

The following section describes the flow control mechanism, which is based on amplification of streamwise vortices. Results of numerical modeling of the flow around the airfoil in presence of the control mechanism, which show the effect of flow control on aerodynamic characteristics of the airfoil, are also presented and compared with those of the base case.

3.1 Flow control mechanism and modeling

Based on the observations described in sections 2.2 and 2.3 regarding the role of the streamwise vortices and their spanwise spacing, an active flow control mechanism consisting of a series of injection ports distributed across the span is designed. By injecting a secondary flow at the desired locations at the trailing edge of the airfoil, the control mechanism generates vorticity that can amplify the streamwise vortices at their natural spanwise wavelength of
\( \lambda_z \), and therefore disorganize and attenuate the von Kármán vortex street. The mechanism consists of 5 rows of 17 injection ports, spaced at a distance of 0.1\( \lambda_z \), covering a total spanwise domain equal to 1.6\( \lambda_z \), as shown in Fig.(9). Each injection port has an area of 0.625 \( \text{mm}^2 \). The upper and lower rows are placed as close as possible to the upper and lower corners of the trailing edge where the shear layer instabilities originate, in order to attain maximum control efficiency.

![Figure 9](image)

Figure 9 : Arrangement of the injection holes at the trailing edge

To make the control system even more efficient and independent of external sources of energy, the idea of conveying the high pressure air from the high pressure area at the nose stagnation region, to the injection ports located at the relatively low pressure area of the trailing edge, is examined. Numerical simulations have been conducted to determine the amount of mass flow rate available for injection by such a design. The resulting mass flow rates determine the available control flow, if no external source of controlling flow is to be used. Results of these numerical simulations, an example of which is shown in Fig.(10), indicate that the best control efficiency in terms of the mass flow rate available for injection and the amount of induced streamwise vorticity, is achieved when only the rows on the top and bottom surfaces of the airfoil are used for injection. The maximum injection velocity that is theoretically attainable in this case is \( 0.75U_{\infty} \approx 7.5 \text{ m/s} \) approximately.

![Figure 10](image)

Figure 10 : An example of pathlines and velocity distribution throughout a channel extending from the nose to the injection holes

The flow control momentum coefficient \( C_{\mu} \), which is defined as the ratio of the momentum injected by the flow control mechanism to the amount of freestream momentum passing through the same section of the flow, is given by the following relation:
\[ C_{\mu} = \frac{\rho U_i^2 na^2}{\rho U_e^2 ab} = \frac{na}{b} \frac{U_i^2}{U_e^2} \]  

In the above relation, \( n \) is the number of injection ports on each side of the airfoil (17 in this case), \( a \) is the effective diameter of each injection port, \( b \) is the span of the airfoil, and \( U_i \) is the injection velocity. Two values of \( C_{\mu} = 1.65\% \) (which corresponds to the maximum achievable injection velocity of 7.5 m/s), and \( C_{\mu} = 0.82\% \) (which corresponds to an injection velocity half of the maximum) are modeled and studied herein.

The numerical model is modified to include the injection holes, modeled as series of individually addressable inlet boundaries. The resulting grid, shown in Fig.(11), has \( 1.76 \times 10^6 \) cells. All other parameters of the numerical simulation are similar to those of the base case.

Figure 10: The grid in at the trailing edge of the airfoil with flow control (inset: detail of the grid around the injection holes)

3.2 Wake characteristics and aerodynamic forces

Results of numerical simulations indicate that the von Kármán vortex street is distorted by the flow control mechanism. Instantaneous isosurfaces of spanwise vorticity (\( \omega_z = \pm 600 \)) are compared in Fig.(11) for the three cases: no control, \( C_{\mu} = 0.82\% \), and \( C_{\mu} = 1.65\% \). The figure indicates that the flow control mechanism leads to out of phase (non-uniform) shedding of spanwise vortices at different spanwise stations for both injection flow rates studied herein.
Figure 11: Instantaneous isosurfaces of spanwise vorticity ($\omega_z = \pm 600$), showing the effect of flow control on the von Kármán vortex street (top: no control, middle: $C_\mu = 0.82\%$, bottom: $C_\mu = 1.65\%$)

This effect is due to the streamwise vorticity that is induced by the flow control mechanism, as shown in Fig.(12). The other effect of the flow control mechanism, which can be observed in Fig.(11) is the increased formation length. The figure indicates that the formation region becomes increasingly elongated when $C_\mu$ is increased from 0 (the base case) to 1.65%. This leads to a larger distance between the core of the spanwise vortices being formed and the base
of the airfoil, which in turn leads to increased values of base pressure and reduced fluctuating aerodynamic forces.

The effect of injection on aerodynamic forces is presented in Fig. (13) and Fig. (14). Time histories of the airfoil’s lift force with and without flow control are shown in Fig. (13). For both values of $C_\mu$, lift force fluctuations are reduced by approximately one order of magnitude, when compared to those of the base (no control) case. Figure (14) compares time histories of the airfoil’s drag force with and without control. A maximum drag force reduction of 40% is achieved by the flow control mechanism. This reduction is slightly larger compared to the one reported by Tombazis and Bearman (Ref. [2]) using spanwise sinusoidal perturbations.
Figure 14: Comparison of time histories of the airfoil’s drag, with and without flow control

Another phenomenon observed in the time histories of aerodynamic forces is the reduced frequency of fluctuations of the forces as a result of flow control. The Strouhal number is 0.150 for $C_\mu = 0.82\%$, and 0.130 for $C_\mu = 1.65\%$. The 44% reduction of the Strouhal number for the $C_\mu = 1.65\%$ case compared to the base case in which $St = 0.23$ is quantitatively comparable to a similar observation by Darekar and Sherwin in Ref. [3].

4 CONCLUSION

Results of numerical simulations of flow around a blunt trailing edge airfoil with and without flow control were presented in the previous sections. The results indicate that the flow control mechanism, which is based on injection of a secondary flow at the trailing edge of the airfoil with a spacing proportional to the natural spanwise spacing of streamwise vortices ($\lambda_z$), results in amplification of streamwise vorticity in the formation region. As a result, the formation region is elongated, and the von Kármán vortex street is disorganized, leading to a considerable decrease in the amplitude and frequency of fluctuating aerodynamic forces.

The effect of the flow control mechanism on aerodynamic forces is best illustrated by the phase averaged lift and drag force diagrams, which are shown in Fig.(15) and Fig.(16), respectively. These diagrams show again that the flow control mechanism can ideally lead to attenuation of lift fluctuations by an order of magnitude, as well as a 40% reduction in the mean drag forces. The phase averaged drag force diagrams of Fig.(16) also indicate that the periodic nature of drag force is greatly disrupted because of the disorganized von Kármán vortex street.
Figure 15: Phase averaged diagrams of the airfoil’s lift, with and without flow control

Figure 16: Phase averaged diagrams of the airfoil’s drag, with and without flow control

5 FUTURE WORK

The efficiency of the flow control mechanism can be further improved by using a reactive flow control concept, in which the secondary flow is injected at those spanwise locations and instances of time at which the streamwise vortices are being naturally formed, instead of using continuous injection. In order to implement such a reactive control mechanism, a flow parameter should be as a trigger. This flow parameter should be correlated with streamwise vorticity.

Results of the presented simulations indicate that spanwise distributions of pressure and the spanwise component of shear stress ($\tau_{xz}$) can be good measures for location of streamwise vortices, as both parameters show good correlation with streamwise vorticity. Fig.(17), in which the phase averaged spanwise distributions of streamwise vorticity and pressure at the
base of the airfoil are compared, is an example of such correlation. It should also be noted that practical aspects such as resolution of pressure or shear stress sensors are also involved in selection of the most appropriate flow parameter for triggering the flow control mechanism.

![Figure 17: Phase averaged spanwise variations of base pressure and streamwise vorticity, showing the anti-phase of the two parameters](image)

REFERENCES


