

Mean velocity development in the asymmetric near wake behind a GAW(2) airfoil

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ABSTRACT

The two-dimensional turbulent asymmetric near wake behind a General Aviation Wing-2 cambered airfoil section is studied at a subsonic speed at zero angle of attack. The near wake flow, which is dictated by the interaction of the on-coming turbulent boundary layers, development has been discussed in this paper. The pressure coefficient distribution on the cambered airfoil has been measured. Mean velocity profile measurements were made in the turbulent near wake flow behind the airfoil. Minimum mean velocity, wake half thickness, momentum thickness and shape parameter based on the streamwise component of mean velocity development in the turbulent near wake are presented here. It is shown that the mean velocity profile which is asymmetric initially near the trailing edge tended to become symmetric as the distance behind the trailing edge was increased. Mean velocity development was seen to display symmetry at a distance of around 60 trailing edge momentum thicknesses from the trailing edge of the model. The focus on near wake flow behaviour with mean velocity profile asymmetry, is motivated by their importance of the high-lift systems utilized in the commercial transport airplane designs. For the asymmetric wake, streamwise evolution of mean velocity are documented in detail. In this manner, the development of wake flow from the initial asymmetry behind the airfoil is isolated.

Keywords: Near wake, GAW(2) airfoil, pressure coefficient, mean velocity, momentum thickness, drag coefficient.

1. INTRODUCTION

Turbulent wake region is the zone of fluid flow after the trailing edge of an object where the upstream turbulent boundary layers, on the upper and lower surfaces, merge into one single shear layer. The near wake is the zone of the turbulent wake fluid flow just after the trailing edge of the body where the fluid flow is greatly influenced by the upstream fluid flow conditions and by the characteristics of the object [Townsend,1956]. In this zone the fluid flow progress takes place with a sudden modification in the boundary condition. It is recognised that, even in the situation where the flow separation is non-existent, the pressure coefficient variation over the rear of streamlined objects is imposed by the collaboration between the turbulent boundary layer, the turbulent wake flow and the external fluid flow [Narasimha and Prabhu,1972; Prabhu and Narasimha,1972]. It is in the near wake zone that the turbulent boundary layers, separated by the upstream rigid surface, coalesce to grow into a single free turbulent shear layer, which is not experiencing any rigid boundary conditions [Srinivasan and Narasimha,1982; Prabhu and Patel,1982; Subaschandar,2005; Subaschandar and Prabhu,1999]. Successful estimation of the performance of objects such as airfoils, turbine and compressor blades and underwater and surface vehicles needs an excellent knowledge of the fluid flow behaviour in the turbulent near wake region. The evaluation and understanding of fluid flow in the turbulent near wake are vital as the fluid flow in this zone is still greatly guided by the upstream trailing edge flow characteristics. Hence the study of fluid flow in this zone represents a significant aerodynamic research problem, especially connected to lift and drag and to estimate the total drag force on the body, it becomes vital to calculate the wake parameters at the downstream edge of the near wake zone [White,2009]. Most of the investigations in the turbulent near wake, theoretical as well as experimental, are limited to the two-dimensional symmetric wake flows behind two-dimensional flat plates and airfoils at low speeds [Andreopolous and Bradshaw,1980; Chevary

and Kovaznay,1969; Ramaprian et al.,1982; Ramaprian et al.,1981; Subaschandar and Prabhu,1999; Subaschandar, 2000; Alber,1980; Bogucz and Walker,1988].

The purpose of the current experimental research is to examine and understand the asymmetric turbulent near wake flow behind a GAW(2) airfoil section which is cambered and developing from the initial asymmetric trailing edge conditions. This kind of asymmetric flow occurs in many situations, for example, the wake flow over and behind the swept wings of airplanes and wake flows generated by the blades of rotor and turbine fans. The near wake problem studied here is one of the simplest examples of asymmetric two-dimensional turbulent near wake fluid flows. Even this simple near wake flow has not been studied widely. The present research is aimed at generating a set of data on the turbulent near wake flow behind a cambered airfoil section and to comprehend the simple asymmetric two-dimensional turbulent near wake growth.

The GAW(2) airfoil section which is a 13% thickness was chosen for this research because of its strong importance in many engineering applications. The GAW(2) airfoil section profile was not changed at all to make the fluid flow less difficult at the trailing edge. The GAW(2) is a cambered airfoil with an asymmetric profile so that the asymmetry existing at the trailing edge is natural, not like the experiments of [(Ramaprian et al 1981, 1982) and Nakayama and Kreplin,1994]. Ramaprian et al [1981,1982] altered the top surface of two-dimensional symmetric flat plate by sticking sandpaper for the entire length of the model. Nakayama and Kreplin[1994] employed a flexible flat plate to get asymmetric flow conditions at the trailing edge. Subaschandar and Prabhu[1999,2002] documented extensively the three-dimensional asymmetric turbulent near wake flow behind an infinitely swept wing with GAW(2) airfoil cross section. Our emphasis in the current study was concentrated in the near wake flow region close to the trailing edge up to a distance of about 75 trailing edge momentum thicknesses downstream of the trailing edge.

The measurements were performed in the asymmetric turbulent near wake behind a GAW(2) airfoil cross section at zero angle of attack. The airfoil is cambered with the turbulent boundary layers on the upper and lower surfaces develop under diverse streamwise pressure gradients and are attached at the trailing edge. The present study would, it is expected, give further push to study more complex asymmetric turbulent near wake flows which frequently occur in engineering applications. The asymmetric near wake flow studied here, being two-dimensional and yet relatively simple, is anticipated to provide a wide understanding of asymmetric near-wake fluid flow features and offer a good and detailed test of the capabilities of various turbulence models, numerical schemes and computational codes which take into account the asymmetry of the fluid flow. Many details regarding the experimental setup, initial conditions and several results were presented in the conference paper by the author of this current manuscript [Subaschandar,2016].

2. EXPERIMENTAL SETUP

The experiments were performed in the 300x1500mm boundary layer wind tunnel of the National Aerospace Laboratories, Bangalore. The GAW(2) airfoil model, with a chord length(C) of 600mm and a span of 300mm, was fixed vertically in the tunnel test section. The airfoil model has a profile thickness of 13.6%. The measurements were conducted at an undisturbed freestream velocity of 30m/s, giving a Reynold number, based on chord length and undisturbed freestream velocity, of 1×10^6 . The measurements were performed at zero angle of incidence. The GAW(2) airfoil is a cambered airfoil and it was not modified at all to avoid fluid flow complications close to the trailing edge. The airfoil model was facilitated with 48 static pressure taps of outer diameter 1.2 mm each on both top and the bottom surfaces along the midspan in the direction of the freestream. The boundary layers on the top and bottom surfaces of the airfoil model were tripped at 10% chord from the leading edge using transition trips (sandpaper of width 15 mm and grade 50). The sandpaper width, grade and location were

chosen to give a fully developed turbulent boundary layer, at the top and bottom surfaces, at the trailing edge of the airfoil model. End plates have been employed at a distance of 10mm from the wind tunnel walls at both ends of the model for attaining the spanwise invariance. Profiles of the magnitude of the local mean velocity vector were measured by employing a pitot probe with a hole radius (outer) of 0.5 mm, along with the static pressure measured in the undisturbed freestream outside the wake. It was noticed that the total pressure measured by the pitot probe was insensitive to the probe inclination up to $\pm 4^\circ$. Mean velocity measurements were performed out in the near wake up to a distance in the range of 1-800 trailing edge momentum thicknesses from the trailing edge. Figure 1 shows the schematic of the experimental setup used to make measurements. Figure 1 displays, also, the coordinate system employed and the mean velocity components. Z-axis which is not shown in the Fig. 1 was perpendicular to the plane of the paper.

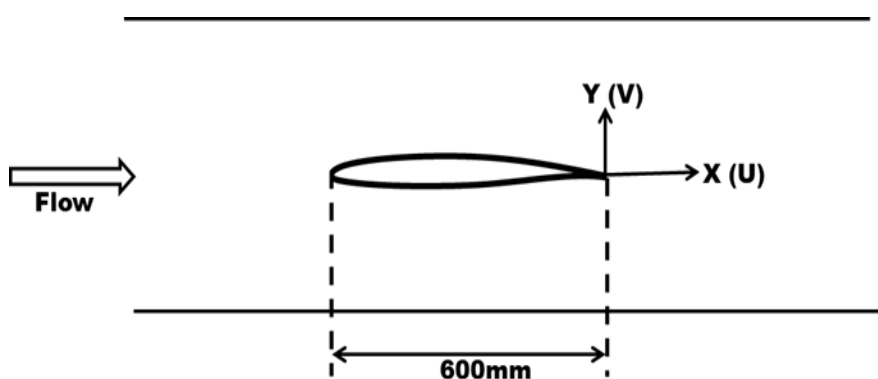


Figure 1: Schematic of the experimental setup (not drawn to scale)

3. INITIAL CONDITIONS

The development of wake flow behind any streamlined object depends on the upstream initial conditions of the fluid flow at the trailing edge of the model. The values of displacement thickness, momentum thickness and shape factor for both upper and lower surfaces of the airfoil model at a location just upstream of the trailing edge of the geometry are given in the Table 1. The integral parameters are calculated based on the streamwise component of mean

velocity. The values of integral parameters on the upper and lower surfaces show the presence of strong asymmetry at the trailing edge.

Table 1: Integral parameters at the trailing edge

Parameters →	$\delta^*(\text{mm})$	$\theta(\text{mm})$	H
Top surface	3.6	2.1	1.534
Bottom surface	0.8	0.5	1.416

Reynolds numbers calculated using total displacement thickness and total momentum thickness near the trailing edge, are about 8700 and 5200 respectively. Although the displacement thickness and momentum thickness Reynolds numbers are not very high, they can be considered to be high enough to provide results independent of Reynolds number. Total drag was computed from pitot-static measurements in the far wake by using the method of Jones[1936] as described in Dos Santos et al[2006] and Schlichting [1979] at three streamwise locations (namely, $X/C=1.5$, 1.75 and 2.0). The total drag coefficient at these three streamwise locations were plotted and shown in the Fig. 2. The graph shows very little difference in the values of total drag coefficients at these three streamwise locations confirming the presence of two-dimensionality in the flow. The mean velocity measurements were carried out in the three horizontal planes along the span (Z -direction) of the model close to the trailing edge (namely, $Z=-75\text{mm}$, $Z=75\text{mm}$ and $Z=0\text{mm}$.) and are presented in the Fig. 3. A very good agreement was seen among the measurements at the three spanwise locations confirming the presence of spanwise invariance of mean velocity profiles.

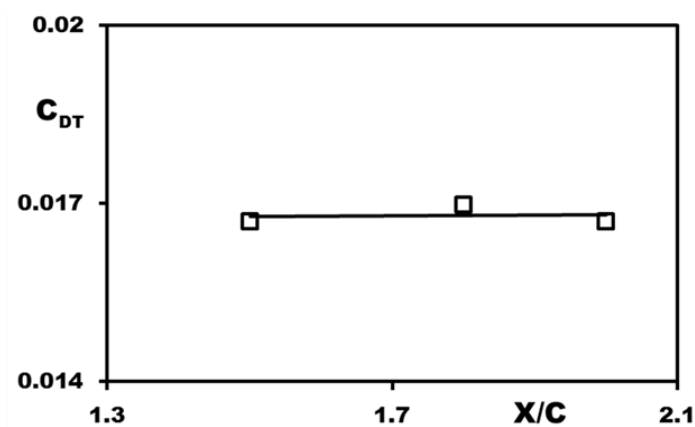


Figure 2: Total drag coefficient calculated using wake survey method at three locations

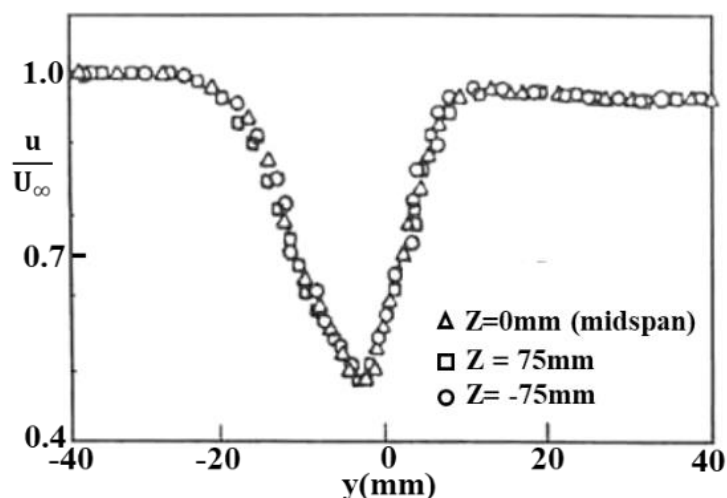


Figure 3: Streamwise component of mean velocity profiles at the three locations along the span of the model close to the trailing edge.

4. RESULTS AND DISCUSSION

In this section, experimental are presented and discussed. Figure 4 presents the static pressure coefficient profile on the cambered airfoil along the chord length. The static pressure coefficient distribution shows that the turbulent boundary layer is only under a moderate adverse streamwise pressure gradient and the fluid flow is attached at the trailing edge of the model. These remarks are reinforced by the fact, as it will be seen later, that the shape factor has a value of about 1.5 at the trailing edge.

Figure 5 shows the progress of streamwise component of mean velocity profiles at various stations in the turbulent near wake. The mean velocity profiles are asymmetric with respect to x-axis and also the minimum mean velocity location begins to shift towards the lower

side of the near wake as the streamwise distance increases. The Mean velocity profiles exhibit a tendency towards symmetrisation by a distance of about 60 trailing edge momentum thicknesses. The location of Y_m where the minimum mean velocity happens is laterally relocated indicating that there was a net lateral (i.e. downward) transfer of momentum within the wake.

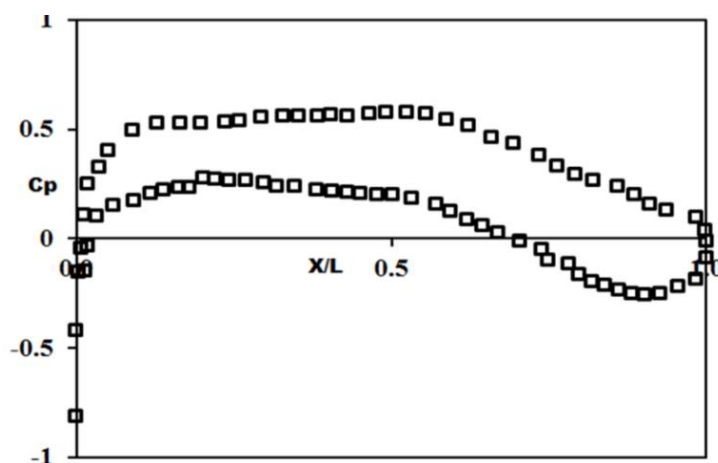


Figure 4: Static pressure coefficient distribution on the airfoil model

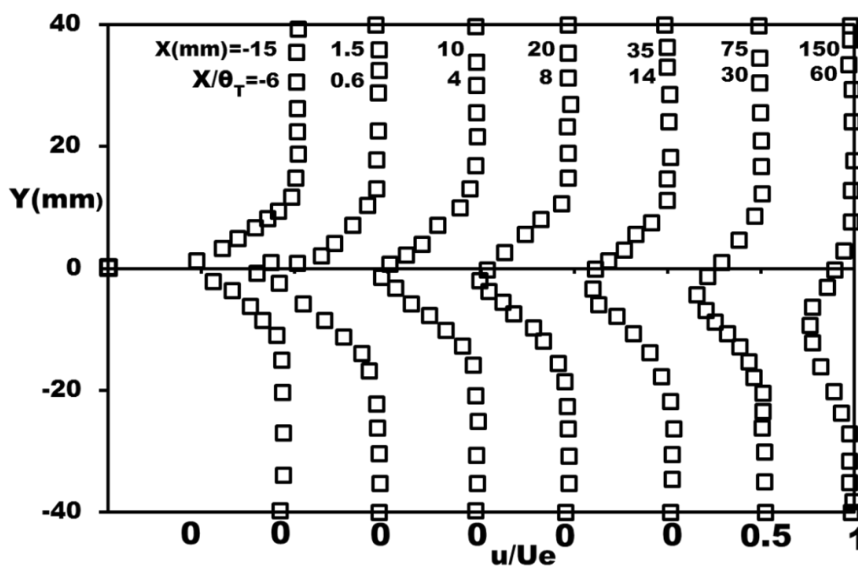


Figure 5: Profiles of streamwise component of mean velocity in the near wake

Figures 6 and 7 show the growth of minimum value of mean velocity and wake half-thickness with streamwise distance in the wake. Wake half-thickness (b) is the sum of the wake half-thicknesses on the upper and lower sides of the wake. Turbulent diffusion makes wake half-

thickness and minimum mean velocity increase rapidly with streamwise distance. Figures 8 and 9 show the growth of momentum thickness and shape factor(H) along the streamwise distance. One can see a rapid decrease in the values of momentum thickness near the trailing edge and thereafter the momentum thickness is almost constant. The shape factor develops quickly in the zone upto $\frac{x}{\theta_T} = 30$, and thereafter the development is slow and by a distance of about 60 trailing edge momentum thicknesses the shape factor only slightly greater than 1, its asymptotic value at very large streamwise distances.

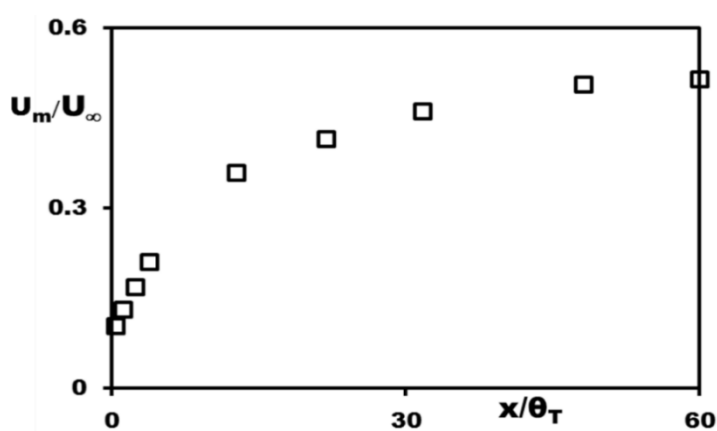


Figure 6: Variation of minimum mean velocity in the near wake

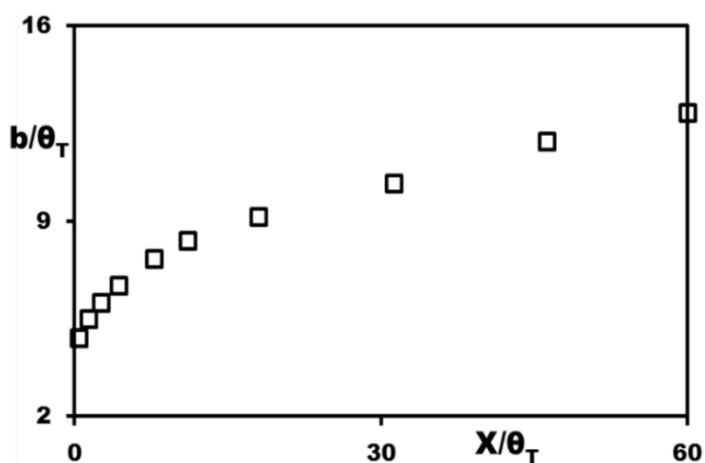


Figure 7: Variation of wake half thickness in the near wake

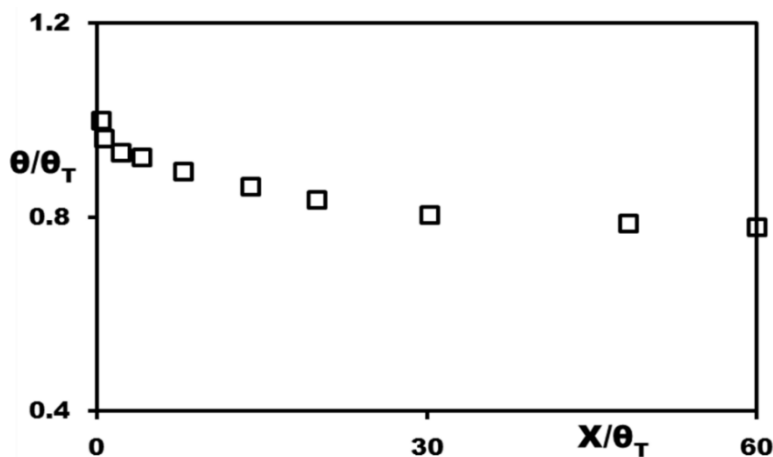


Figure 8: Variation of momentum thickness in the near wake

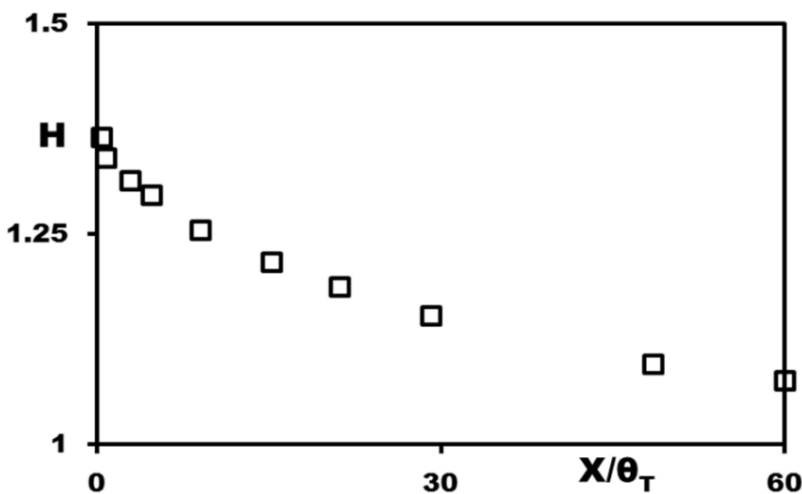


Figure 9: Variation of shape parameter in the near wake

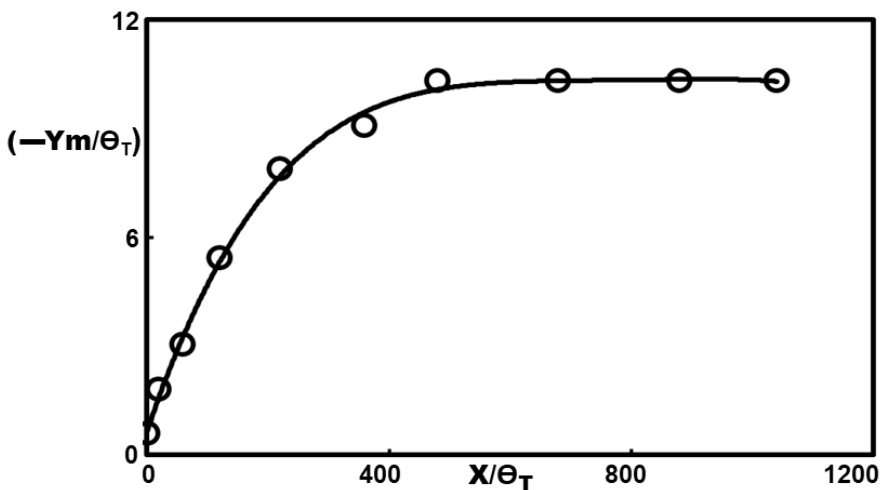


Figure 10: Movement of minimum mean velocity location in the near wake

Figure 10 shows the movement of the location of the minimum value of the streamwise component of mean velocity (Y_m) with the streamwise distance. It should be noted that the

minimum value locations moved below the tunnel centreline and, hence, negative values of (Y_m) have been plotted with streamwise distance in this graph. One can observe that the location of the minimum value of the streamwise component of mean velocity rapidly moves downwards near the trailing edge upto a distance of nearly 500 trailing edge momentum thicknesses and thereafter further downward movement of (Y_m) stops and the location of (Y_m) remains nearly the same. This downward movement of the location of the minimum value of the streamwise component of mean velocity does indicate a net downward transfer momentum in the wake. The starting region where the downward movement of (Y_m) stops, which is about 500 trailing edge momentum thicknesses from the trailing edge, is likely to be the start of the region where the fluid flow starts to become self-similar. However, this behaviour of the fluid flow in the wake must be investigated further.

In summary, the experimental data in the turbulent wake behind a GAW(2) airfoil indicate that the mean velocity profiles show a tendency toward symmetrisation around a distance of 60 trailing edge momentum thicknesses from the trailing edge. The results presented in this paper not only would be useful to validate various turbulence models, numerical schemes and computational codes, but also, provide impetus to research on more complex asymmetric near wake flows involving, perhaps, large separation regions near the trailing edge, high angle of attack, three-dimensionality and very large Reynolds numbers.

5. CONCLUSIONS

Mean velocity measurements have been carried out in the asymmetric near wake flow region behind a GAW(2) airfoil at low speeds at zero angle of attack. Profiles of mean velocity exhibit asymmetry close to the trailing edge and show a tendency toward symmetrisation around a distance of 60 trailing edge momentum thicknesses. The present experiments indicate that far-wake structure has not been attained within a distance of 60 trailing edge momentum thicknesses. The location of the minimum value of the streamwise component of mean velocity

in the near wake rapidly moves downwards near the trailing edge upto a distance of nearly 500 trailing edge momentum thicknesses and thereafter further downward movement of (Y_m) stops and the location of (Y_m) remains nearly the same. It is the region where the fluid flow in the wake starts to become self-similar is likely to be about 500 trailing edge momentum thicknesses from the trailing edge. However, this behaviour of (Y_m) must be investigated further. The results presented in this paper not only would be useful to validate various turbulence models, numerical schemes and computational codes, but also, provide impetus to research on more complex asymmetric near wake flows.

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DECLARATION OF COMPETING INTEREST

The author declares that he does not have any competing financial interests or personal relationships that could appear to influence the work reported in this paper.

REFERENCES

- [1]. Townsend, A.A. (1956) 'The Structure of Turbulent Shear Flow'. Cambridge University Press, Cambridge, U.K.
- [2]. Narasimha, R. and Prabhu, A. (1972) 'Equilibrium and relaxation in turbulent wakes', Journal of Fluid Mechanics, 54(1), pp. 1–17. <https://doi.org/10.1017/S0022112072000497>.
- [3]. Prabhu, A. and Narasimha, R. (1972) 'Turbulent non-equilibrium wakes', Journal of Fluid Mechanics, 54(1), pp. 19–38. <https://doi.org/10.1017/S0022112072000503>.
- [4]. Sreenivasan, K. R., and Narasimha, R. (1982) 'Equilibrium Parameters for Two-Dimensional Turbulent Wakes', ASME Journal of Fluids Engineering, 104(2), pp. 167–169. <https://doi.org/10.1115/1.3241801>
- [5]. Prabhu, A. and Patel, V.C. (1982) 'Analysis of turbulent near wakes', IIHR Report No. 253, University of Iowa, U.S.A.
- [6]. Subaschandar, N. (2005) 'Measurements in the Turbulent Near-wake Behind an infinitely swept Flat Plate', Journal of Experimental Thermal and Fluid Science, 29(4), pp. 415-423. <https://doi.org/10.1016/j.expthermflusci.2004.04.003>.

- [7]. White, F.M. (2009) 'Viscous Fluid Flow', 7th Edition, McGraw-Hill, McGraw-Hill Companies, Inc., New York, USA. www.mhhe.com. ISBN 978-0-07-352934-9.
- [8]. Andreopoulos, J. and Bradshaw, P. (1980) 'Measurements of interacting turbulent shear layers in the near wake of a flat plate', *Journal of Fluid Mechanics*, 100(3), pp. 639–668. <https://doi.org/10.1017/S0022112080001322>.
- [9]. Chevray, R. and Kovasznay, L. S. G. (1969) 'Turbulence measurements in the wake of a thin flat plate.', *AIAA Journal, American Institute of Aeronautics and Astronautics*, 7(8), pp. 1641–1643. <https://doi.org/10.2514/3.5461>.
- [10]. Ramaprian, B. R., Patel, V. C. and Sastry, M. S. (1982) 'The symmetric turbulent wake of a flat plate', *AIAA Journal, American Institute of Aeronautics and Astronautics*, 20(9), pp. 1228–1235. <https://doi.org/10.2514/3.7972>.
- [11]. Ramaprian, B. R., Patel, V. C. and Sastry, M. S. (1982) 'Turbulent Wake Development behind Streamlined Bodies', Iowa Institute of Hydraulic Research Report 231, University of Iowa, USA.
- [12]. Subaschandar, N. and Prabhu, A. (1999) 'Turbulent near-wake development behind a flat plate', *Journal of Aerospace Science and Technology*, 1(2), pp. 61–70. [https://doi.org/10.1016/S1270-9638\(99\)80030-3](https://doi.org/10.1016/S1270-9638(99)80030-3).
- [13]. Subaschandar, N. (2000) 'Prediction of turbulent near and far wake flows using four turbulence models', *Computational Fluid Dynamics Journal*, 8, pp. 544–560, 2000. <https://ci.nii.ac.jp/ncid/AA10930387?l=en#anc-resource>.
- [14]. Alber, I. E. (1980) 'Turbulent Wake of a Thin, Flat Plate', *AIAA Journal, American Institute of Aeronautics and Astronautics*, 18(9), pp. 1044–1051. <https://doi.org/10.2514/3.50853>.
- [15]. Bogucz, E.A. and Walker, J.D.A. (1988) 'The turbulent near wake at a sharp trailing edge', *Journal of Fluid Mechanics*, 196, pp. 555–584. <https://doi.org/10.1017/S0022112088002812>.
- [16]. Nakayama, A. and Kreplin, H.P. (1994) 'Characteristics of asymmetric turbulent near wakes', *Physics of Fluids*, 6(7), pp. 2430–2439. <https://doi.org/10.1063/1.868190>.
- [17]. Subaschandar, N. and Prabhu, A. (2002) 'Turbulent Near-Wake Studies Behind an Infinitely Swept Wing', *Journal of Aircraft, American Institute of Aeronautics and Astronautics*, 39(2), pp. 290–295. <https://doi.org/10.2514/2.2926>.
- [18]. Subaschandar, N. and Prabhu, A. (1999) 'Turbulent near wake behind an infinitely swept wing', 8th Asian Congress of Fluid Mechanics, Shenzhen, CHINA, Dec 6-10, 1999.
- [19]. Subaschandar, N. (2016) 'Mean Velocity in the Asymmetric near Wake Behind a GAW(2) Airfoil', *MATEC Web of Conferences* 54, 11002. <https://doi.org/10.1051/mateconf/20165411002>.
- [20]. Jones, B.M. (1936) 'The Measurement of Profile Drag by the Pitot-Traverse Method', *ARC Reports and Memoranda No. 1688*, Teddington, UK.
- [21]. Dos Santos, L.A., Avelar, A.C., Chiseaki, M. and Mello, O.A.F. (2006) 'Drag estimation by wake survey performed measuring velocities and measuring total and static pressures', *Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering-ENCIT 2006*, Curitiba, Brazil, Dec. 05-08.
- [22]. Schlichting, H. (1979) 'Boundary Layer Theory', 7th Edition, McGraw-Hill Book Co., New York.