AIAA JOURNAL
Vol. 40, No. 6, June 2002

Large-Scale Structures and Growth of a Flat Plate Compressible Wake

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Experiments conducted on a flat plate wake in a compressible flow at Mach 2 are described. Large-scale organized motions are revealed both in the separating boundary layer upstream and in the wake downstream. The organized motions in the wake contained within them embeded vortex structures, whose periodicity was found to be weak. The broadband spectra contained a distinct frequency with a Strouhal number of 0.3. The study of mean flow characteristics showed that some qualitative similarity exists in the near- and intermediate-wake regions. The relative Mach number distribution showed the compressibility effects to be small.

I. Introduction

ORGANIZED structures in turbulent compressible shear and mixing layers have been extensively studied in recent years, for example, by Papamoschou and Roshko,[1] Dolling et al.,[2] Clemens and Mungal,[3] Shau et al.,[4] Barre et al.,[5] and Clemens et al.[6] Their existence in compressible turbulent boundary layers has also been verified and elucidated by Spina and Smits,[7] Smits et al.,[8] Spina et al.,[9] and Zhong and Squire.[10,11]

The related problem of large-scale structures in compressible wakes has received comparatively less attention. The most notable contributions to the literature in this area are those of Bonnet et al.,[12] Bonnet and Chaput,[13] Althaus,[14] and Smith and Dutton.[15]

Whereas Bonnet et al.[12] and Bonnet and Chaput[13] investigated the compressible wake evolved from a thin plate having negligible trailing-edge thickness at a Mach number of 2, the investigation by Smith and Dutton[15] is concerned with the near-wake flow including blunt base effects. The work of Althaus,[14] on the other hand, deals with the investigation of a turbulent flat plate wake at a Mach number of 2, with emphasis on wake flow structure and its development depending on whether the plate surface is rough or smooth. His results seem to suggest that the growth and structure of the wake depended on the characteristic thickness of the separating boundary layer. However, the evidence is not conclusive. The characteristic thickness is defined as the ratio of the separating boundary-layer thickness to the finite trailing-edge thickness.

In this study, the compressible wake from a flat plate is investigated at a freestream Mach number of 2. The emphasis is on the organized motions in such a wake, as well as the study of its growth and analysis of some of the growth characteristics. Although a number of studies exist of incompressible turbulent flat plate wake flows,[16–18] data concerning compressible turbulent flat plate wakes are sparse, as pointed out by Bonnet et al.[12]

II. Experimental Details and Techniques

A. Wind Tunnel and Model

All of the experiments were conducted in a supersonic blowdown wind tunnel having a 150-mm (height) and 90-mm (width) cross section at a freestream Mach number of 2.0. During the experiments, while the stagnation temperature was ambient and remained approximately constant within ±1%, the stagnation pressure could be varied to vary the Reynolds number. The variation of stagnation pressure from 135 to 440 kPa gave the unit Reynolds number Re/m in the range 30×10^6–100×10^6, and the corresponding run times varied between 30 and 10 s. The stagnation pressure was kept constant during a run within ±10 kPa, resulting in the accuracy of the unit Reynolds number of ±4%. The majority of the tests were conducted at stagnation pressures between 300 and 400 kPa.

The flat plate model producing the wake was a thin splitter plate aligned with the longitudinal axis of the wind-tunnel test section that protruded upstream of the supersonic nozzle throat into the subsonic portion, thus dividing the flow symmetrically. The flat plate had a streamlined section with a rounded leading edge and a trailing edge of approximately 1 mm thick. The plate spanned the 90 mm width of the test section and had a chord of 480 mm. The test section and the plate are shown in Fig. 1.

The boundary layer at the trailing edge of the plate was measured with a traversing pitot probe, which incorporated a Kulite XCQ-062 miniature pressure transducer. The measurement station was 3 mm upstream of the trailing edge.

Depending on the Reynolds number, the boundary-layer thickness at the trailing edge varied from 6.73 mm (±0.1 mm) to 5.5 mm (±0.1 mm). The corresponding momentum thickness at the trailing edge varied from 0.634 to 0.550 mm. The profile was close to the $\frac{1}{7}$th power law profile. These values compared well with those calculated using the relation of Crocco and Lees,[19] valid for a wide range of Reynolds numbers and turbulent boundary layers. Their expression is as follows:

$$\delta = 0.037c(Re_c)^{-\frac{1}{5}}(C_{fm}/C_{fi})(\delta^{**}/\delta)^{-1}$$

where δ is the boundary-layer thickness at the trailing edge of the plate, c is the length of the plate, Re_c is the Reynolds number based on c and freestream conditions, and δ^{**} is the momentum thickness. The factor (C_{fm}/C_{fi}) is the compressibility correction. Crocco and Lees[19] give values of (C_{fm}/C_{fi}) and (δ^{**}/δ) as a function of Mach number. Based on this relation, the boundary-layer thickness at the trailing edge of the plate varies from 6.83 to 5.41 mm, which compares favorably with the experimental values. The Reynolds number Re_c during the tests ranged between 26×10^6 and 59×10^6, which was always sufficiently greater than the value $Re_c = 12 \times 10^6$, often quoted as the transition Reynolds number for ensuring a turbulent boundary layer at the trailing edge.[19]

As noted earlier, the ratio of the trailing-edge thickness to momentum thickness varied from 1.58 to 1.82. Note that the corresponding value with the splitter plate boundary layers laminar was 2.33 during the experiments of Clemens and Smith,[20] who studied transition in a compressible flat plate wake using a similar experimental arrangement. Furthermore, observations of the variations of this parameter with base pressure for incompressible flow with a turbulent separating boundary layer[21] suggests that thickness effects of the trailing edge in the present instance are not too significant.

Received 17 July 2001; revision received 15 October 2001; accepted for publication 10 December 2001.

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B. Flow Visualization

A spark schlieren system was used for visualizing the boundary layer and the wake. The spark source had a duration of 100 ns. During a single pulse, the flow convection distance is of the order of 0.1 mm so that features such as turbulent structures could be reliably observed. The schlieren system employed both horizontal and vertical knife edges.

The optical windows in the side walls of the test section had a diameter of 155 mm. This enabled the observation of about 130 mm of the wake and about 25 mm length of the boundary layer on the plate. To visualize both streamwise and spanwise flows, two sets of models, one mounted horizontally (streamwise) and one mounted vertically (spanwise), were used.

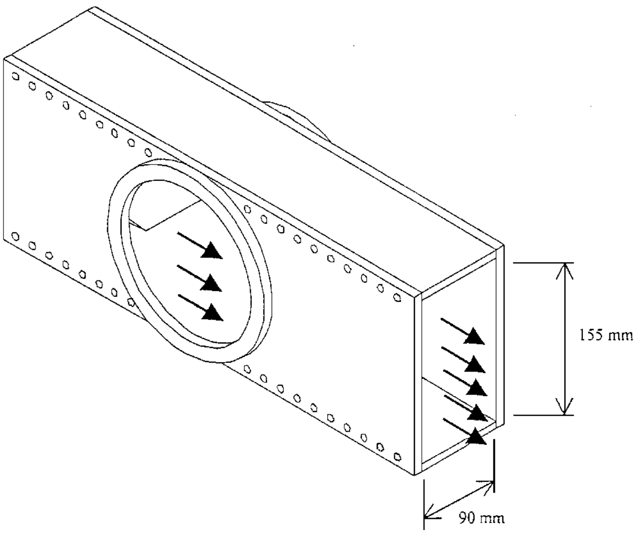


Fig. 1a Test section.

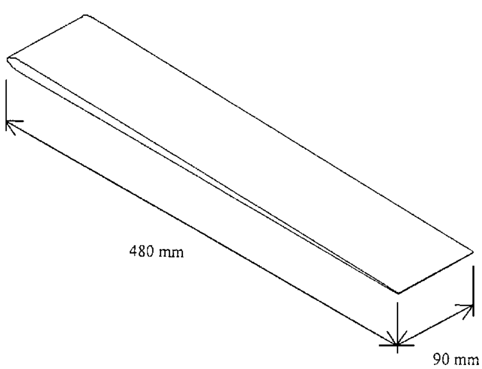


Fig. 1b Plate.

C. Pitot Pressures and Velocity Profiles

Pitot pressure profiles and, hence, the velocity profiles were obtained in the boundary layer and the wake. Pitot pressures were measured with a pitot tube that was equipped with a miniature Kulite semiconductor (Type XCQ-062) pressure transducer housed within it. With the pitot tube arrangement, streamwise positions between $x = -10$ and 72 mm could be covered, where x is measured positive downstream from the trailing edge in the streamwise direction. The vertical traverse y at any given streamwise position was controlled by a stepper motor. Inputs from both the transducer and the stepper motor were controlled using a computer. From the pitot traverses, velocity profiles were obtained using the Rayleigh relation combined with the assumption of constant stagnation temperature across the boundary layer and the wake.

D. Static Pressure Fluctuation Data

The aim of the static pressure fluctuation measurements was to examine the spectra to identify whether there were any dominant or preferred frequencies of organized motions existing in the boundary layer and the wake. The use of pressure probes, either pitot or static, to investigate large-scale structures in shear layers has been shown to be comparable to hot-wire measurements by Parthasarathy et al.,[22] Shau and Dolling,[23] and Samimy et al.[24]

The static pressure fluctuations were measured in the wake at a position $x = 130$ mm downstream and $y = 6$ mm, approximately near the edge of the shear layer. A Kulite semiconductor (XCQ-062 Series) miniature pressure transducer mounted at the tip of a probe oriented perpendicular to the flow direction was used for this purpose. The transducer, whose outer diameter was 1.57 mm and whose sensor area was 0.46 m^2, was set in the differential mode, where the backpressure line was connected to the freestream static pressure port. The freestream static pressure port was located in the side wall of the test section 73 mm upstream of and 12 mm above the trailing edge. The transducer had a range of 0–689.5 kPa with a sensitivity of 0.1586 mV/kPa and a natural frequency of 100 MHz. The amplified output signal from the transducer was fed into a dual channel fast Fourier transform analyzer to process and store the data. The data were sampled at a 100-kHz sampling rate. For each stagnation pressure setting, 128 samples were obtained and all of these were then averaged to obtain a consistent set of data. All of the spectra displayed were unfiltered.

III. Results and Discussion

A. Frequency Spectra of Pressure Fluctuations

Frequency spectra obtained with the Kulite pressure transducer 130 mm downstream at the edge of the wake are shown in Fig. 2.

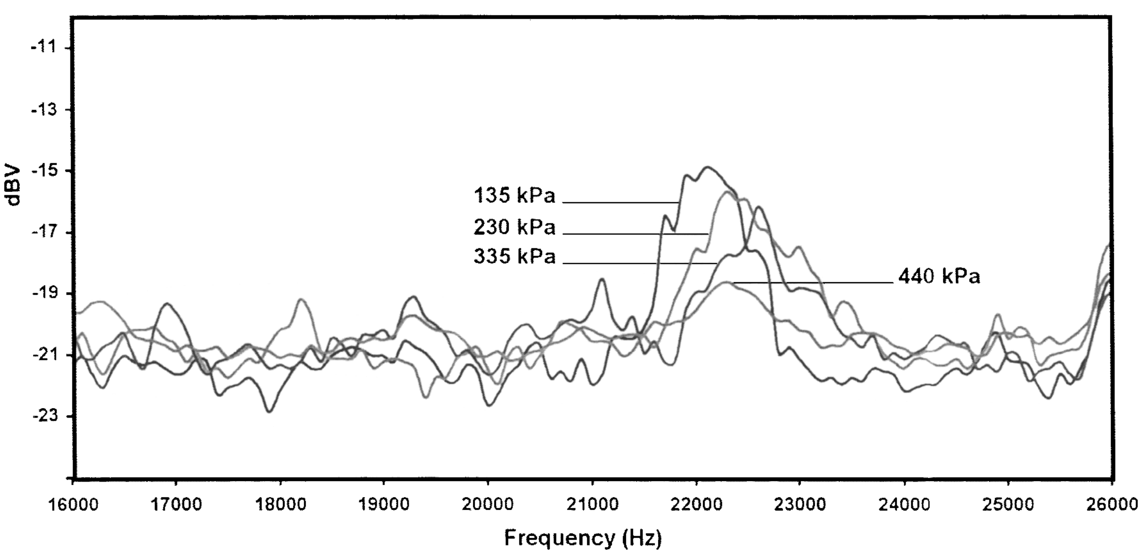


Fig. 2 Frequency spectra of static pressure fluctuations at $x = 130$ mm downstream of the trailing edge.

The objective of these static pressure fluctuation measurements was to identify whether there are any dominant or preferred frequencies of the wake and not the measurement of pressures per se.

Spectra obtained at four values of stagnation pressure are shown in Fig. 2, overlaid on one graph in the frequency range 16–26 kHz. Before obtaining these results, spectra with no flow showed two peaks at 15.5 and 26 kHz, which were identified as due to electrical noise sources in the laboratory. Now, corresponding to the stagnation pressure of 135 kPa ($Re/\mathrm{m} = 30 \times 10^6$), it is evident that the spectra is broadband, although a distinct frequency can be identified at 22 kHz. It is not very sharp, indicating that the periodicity of flow structures is weak. It is further seen that there is some reduction in amplitude and also a slight increase in frequency with increasing stagnation pressure up to 335 kPa after which there seems to be slight reduction in the value of peak frequency. The reduction in the spectral peaks and the broadband spectra implies that any organized vortex structures are weak, which is unlike those observed in incompressible wakes. Similar phenomena in supersonic turbulent free mixing layers have been noted by Ikawa and Kubota,[25] who found that the peak in the spectra disappeared with increasing Reynolds number and with increasing boundary-layer trip roughness. On the other hand, Althaus[14] found that, at a given Mach number, the appearance of vortex structures depended on whether the trip roughness exceeded a critical value and also on whether the distance between the trailing edge and the roughness trip was of the order of boundary-layer thickness at the trailing edge.

Motallebi and Norbury[26] also found that, at moderate supersonic Mach numbers, hot-wire signals exhibited low-amplitude periodicity and that their schlieren photographs of the near wake of a blunt base exhibited vortexlike structures. It is well known[14,27,28] that vortex shedding is weak in supersonic flows. Althaus[28] shows from stability criteria that high Mach numbers stabilize the wake by reducing the length of the locally absolutely unstable region and that the probability of finding vortices in the wake of a flat plate is proportional to the length of this region. Althaus[14] also notes that the vortex shedding frequency is inversely proportional to both the momentum thickness of the wake and the plate thickness. Althaus[28] also shows that vortex shedding frequency is considerably higher for supersonic than subsonic flows. Distinct vortex shedding is also seen in the compressible flat plate wake photographs of Clemens and Smith,[20] although the separating boundary layer in this case was laminar, and transition occurred downstream in the wake, where two-dimensional vortex shedding decayed into a three-dimensional turbulent flow.

The Strouhal number based on the characteristic shear layer thickness, the dominant frequency, and the freestream velocity is 0.3. The existence of such vortex structures has also been noted in free turbulent mixing layers by Shau et al.,[4] Clemens et al.[6], and Ikawa and Kubota.[25]

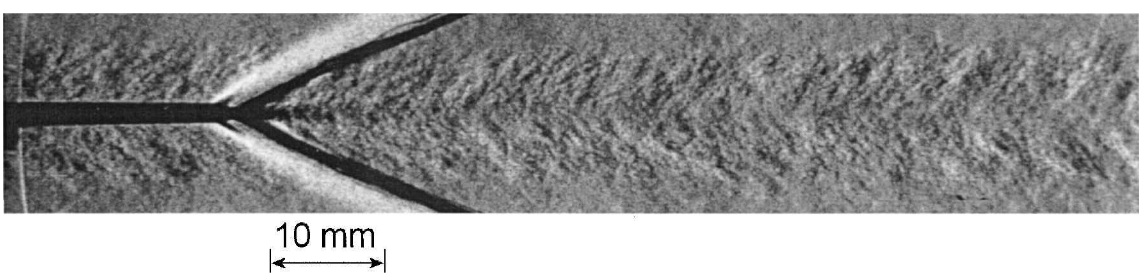
The results of Bonnet et al.[12] and Bonnet and Chaput,[13] on the other hand, do not exhibit any distinct vortex shedding, nor do these authors explicitly discuss vortex shedding in a flat plate compressible wake. Their laser-planogram photographs of the near wake do not show any clear indication of vortex shedding either.

In a recent paper, Lysenko[29] has shown that the wake power spectra exhibit a characteristic frequency and its higher-order harmonics depending on how transition occurs in the wake. The occurrence of transition seemed to depend on the unit Reynolds number, the Mach number, and the plate thickness. The transition moved upstream toward the trailing edge with an increase of the unit Reynolds number and plate thickness but with a decrease of the Mach number. Transition also moved upstream with the introduction of disturbances generated at the plate. In particular, the appearance of higher-order harmonics depended on the nonlinear growth of disturbances in the wake. These results are consistent with the earlier findings by Behrens and Ko,[30] Behrens et al.,[31] and Althaus.[14] Behrens et al.[31] further showed that in a turbulent wake a pronounced peak in the spectrum also develops but mostly the spectrum is broadband. This behavior is consistent with the present data. Note that, in the present experiments, the unit Reynolds numbers are many times larger than in the experiments of Lysenko,[29] Behrens and Ko,[30] and Behrens et al.[31] and that the separating boundary layer is turbulent. Lysenko[29] and Behrens and Ko[30] also found that, in transitional wakes, the Strouhal number based on the peak frequency, the wake width, and the external velocity was approximately 0.3, similar to the present findings.

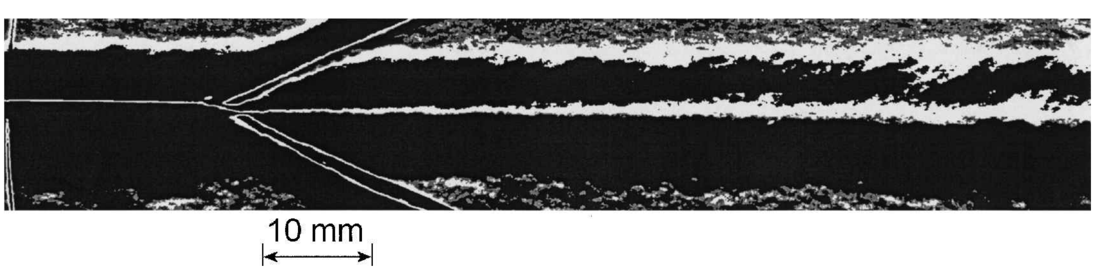
B. Organized Motions

Bonnet and Chaput[13] provide laser planogram pictures of a supersonic flat plate wake at a Mach number of 2 and found that, although large-scale structures exist in the far wake, no detectable large-scale structures could be seen in the near wake.

Figures 3a and 3b show two schlieren images of the present flat plate wake in a Mach 2 flow. The Reynolds number of the flow was about 44×10^6. In Fig. 3a, the knife edge is vertical so that density gradients in the streamwise direction are shown. Both the boundary layer on the plate and the wake downstream of the trailing edge are clearly seen. An expansion fan is followed by a compression wave at the trailing edge. There is also an indication of periodic vortex shedding immediately behind the trailing edge. The presence of this periodic vortex shedding seems to persist for about six plate thicknesses downstream.

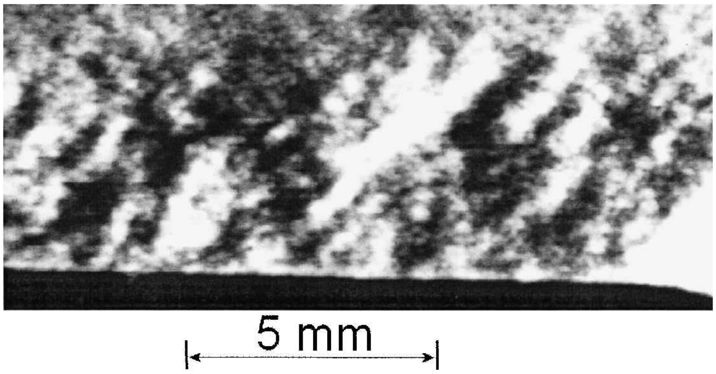


a) Knife edge, vertical

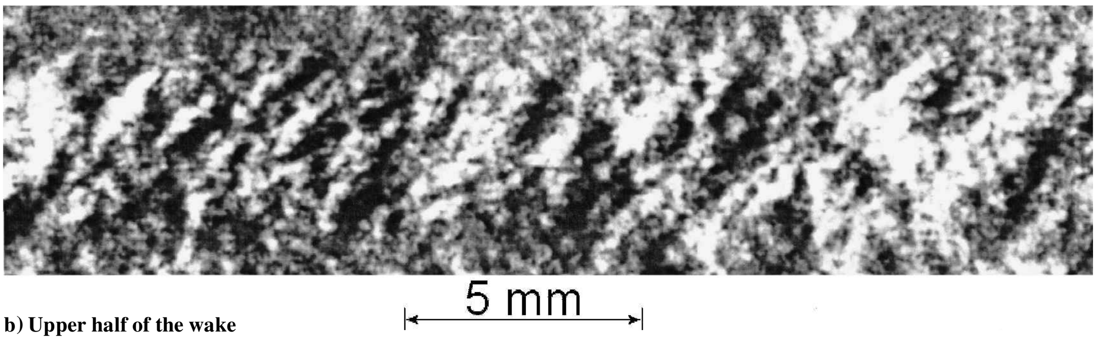


b) Knife edge, horizontal

Fig. 3 Spark schlieren images of the boundary layer and the wake (flow from left to right).



a) Boundary layer



b) Upper half of the wake

Fig. 4 Magnified images showing inclined structures (flow from left to right).

The photographs of Fig. 3a, with the knife edge vertical, clearly show inclined large-scale structures both in the boundary layer and in the wake. These structures are seen to be convected from the boundary layer into the wake and go through the expansion and compression wave system at the trailing edge relatively undistorted. The scale of these structures is on the order of the boundary layer and shear layer thicknesses.

Figure 3b, with the knife-edge horizontal, also shows structures in the boundary layer and the wake, although not as distinctly as that with the knife-edge vertical. However, with the knife-edge horizontal, the smaller scale structures are better highlighted, and it is seen that large-scale structures appear more braidlike and seem to be made up of layered smaller scale structures.[32] The boundary layer and the wake edge are both quite well defined.

Figures 4a and 4b are the magnified images of these inclined structures in the boundary layer and the wake, respectively. In Fig. 4a, the boundary-layer structures are quite distinct and are inclined approximately 45 deg to the streamwise direction. The upper half of the wake (Fig. 4b) also shows that the structures are approximately inclined 45 deg to the flow direction. Close to the axis, they seem to be more upright.

The inclined structures seen in Figs. 4a and 4b have been noted previously in supersonic boundary layers by Spina and Smits,[7] Spina et al.,[9] and Zhong and Squire.[10,11] They have been identified in compressible mixing layers by Shau et al.[4] and Clemens et al.[6] They have also been observed in wakes behind blunt bodies in supersonic flow.[15,26,27] Spina et al.[9] and Zhong and Squire[10,11] have noted that the basic shape of these structures remained invariant with Reynolds number. Increasing the Reynolds number merely increased the number of scales without altering the basic structure.[9]

The alternative dark and bright regions of the density field in Figs. 3a or 4b suggest embedded vortex structures. This was also anticipated from the static pressure fluctuation measurements described in Sec. III.A. The existence of such inclined vortex structures in a compressible flat plate wake has also been numerically predicted by Chen et al.,[33] who showed that the combined effect of baroclinic torque and vortex stretching mechanisms in a viscous compressible fluid prevents vortices from rolling up, but instead produces vortices that are elongated and flattened in appearance and oriented along the diverging separatrix in the saddle region.

Figure 5 confirms the existence of a vortex street immediately behind the trailing edge of the plate and also shows the outline of the vortex structures. Figure 5 is a processed image of the schlieren image using ADOBE Photo Delux software.

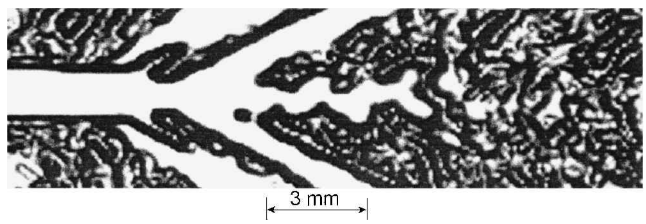


Fig. 5 Processed image of the near wake showing vortex street.

Because both schlieren and interferometry techniques involve integration along the optical path, there is always the uncertainty as to whether the resulting images represent the true state of turbulence and its dynamics. However, Zhong and Squire[10] have shown, by comparing numerical predictions from a large-eddy simulation to the actual structures in a supersonic turbulent boundary layer, that these instantaneous optical visualizations do represent the turbulent structure. Also, recent studies by Urban et al.[34] have shown that instantaneous scalar visualizations correspond closely with instantaneous velocity fields.

Figure 6 shows the schlieren image of the spanwise flow in the wake. The picture was taken with the knife-edge horizontal so that spanwise density gradients are visible. Because these gradients are small, the details of the vortex structures are not clearly evident. However, the spanwise coherence of the structures is evident.

C. Overall Characteristics

1. Wake Growth and Similarity

Wake profiles were obtained using a pitot probe traverse, as stated in Sec. II. The measurement station nearest to the trailing edge was 4 mm downstream of the trailing edge, and the farthest station was 72.5 mm from the trailing edge. From the velocity profiles, the wake momentum thickness θ was determined to be 0.55 mm ± 0.1 mm at all measurement stations.

The visual growth of the wake as measured from the schlieren photographs varied from 10 to 11.5 mm in the measurement range from $x/\theta = 7.3$ to 132, showing the growth rate to be small.

There have been a number of studies[12,30] that have recorded the mean flow properties of a turbulent compressible flat plate wake.

All of these studies emphasize that the asymptotic properties of the compressible turbulent wake are essentially similar to the incompressible wake. Inferences about the behavior of a compressible wake are then drawn based on their comparison with the incompressible wake data.[12,30]

Following Ramaprian et al.,[17] Bonnet et al.[12] delineate various regions of the wake, a near-wake region where $0 < x/\theta \leq 25$, an intermediate-wake region where $25 \leq x/\theta \leq 300$, and a far-wake region where $x/\theta > 300$. Note that in the near-wake region there is a rapid increase in both the wake half-width b and the wake center line velocity U_c, whereas in the intermediate-wake region, the rates of increase of b and U_c are slower with the mean velocity profiles exhibiting some qualitative similarity. In the far-wake region, the profiles attain full similarity. The accelerated growth rate seen by Bonnet et al.[12] in the near- and intermediate-wake regions is also seen in incompressible flat plate wake.[16,17]

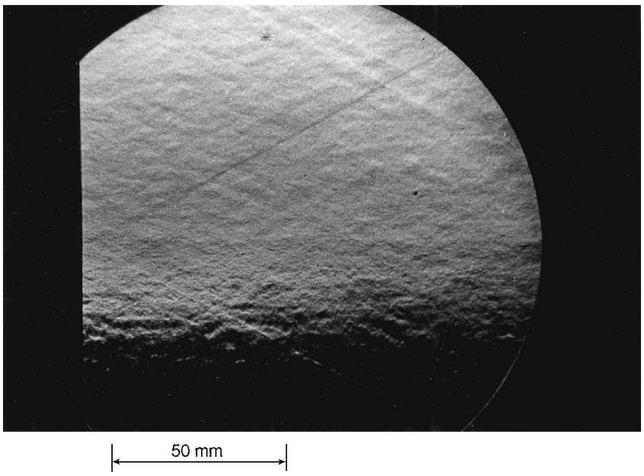


Fig. 6 Schlieren image of the spanwise flow in the wake.

Figure 7 shows the wake growth in terms of the wake half-width as a function of downstream distance for the present experiments. The data are plotted in terms of similarity scaling parameters $(b/\theta)^2$ as a function of (x/θ). A least-squares fit is drawn through the data points corresponding to velocity profiles measured at various downstream locations from the trailing edge. In spite of the large scatter and small number of points, Fig. 7 shows that $(b/\theta) \sim (x/\theta)^{1/2}$ scaling exists in the near- and intermediate-wake regions. Also shown in Fig. 7 are the results of Bonnet et al.[12] and the incompressible asymptotic far-wake relation.[17]

The present results, however, although in general agreement with those of Bonnet et al.,[12] differ from those of Nakagawa and Dahm,[35] who found that the virtual origin (x_0/θ) exists downstream of the trailing edge. They attributed such a behavior to the expansion/recompression process behind a blunt base. Note that their experimental arrangement involved a blunt base through which a weak jet issued, resulting in a near wake that was dominated by jet mixing. Their attempt at comparison of such a flow with self-similar planar turbulent wake properties, therefore, seems difficult to justify.

2. Relative Mach Number

Relative Mach number is a way of quantifying the level of compressibility in the wake.[20,35] Its role is similar to that of the convective Mach number in compressible mixing layers. The relative Mach number is defined as

$$M_r = (U_\infty - U_c)/a_\infty$$

where U_∞ is the freestream velocity, U_c is the velocity on the wake axis, and a_∞ is the freestream speed of sound.

The relative Mach number in the wake could be determined from the velocity profile data obtained as described earlier. Figure 8 shows that the relative Mach number decreases with increasing downstream distance and that, correspondingly, the effects of compressibility are reduced. As a point of comparison, in the

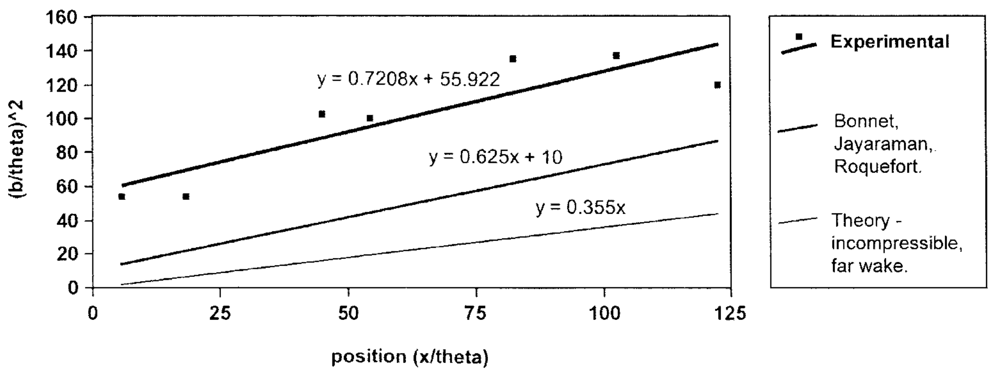


Fig. 7 Wake growth with downstream distance.

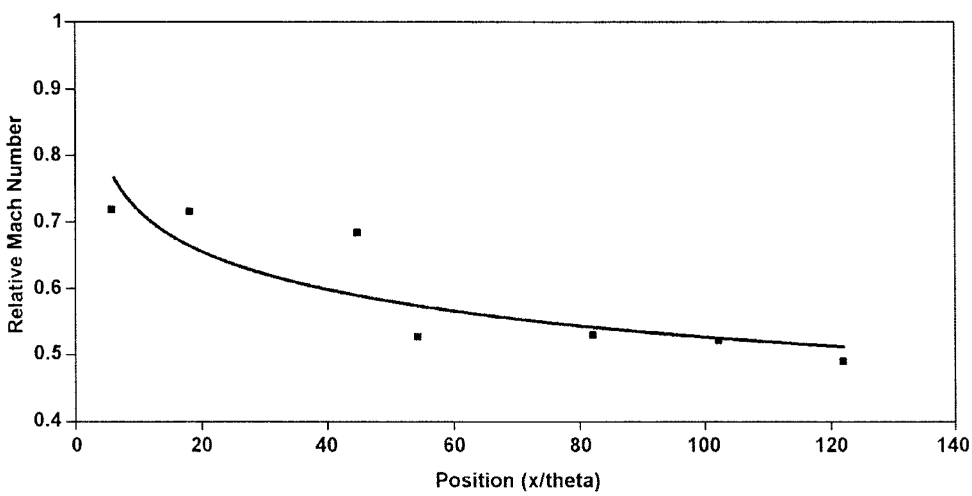


Fig. 8 Relative Mach number variation in the wake.

range $x/\theta = 25$–120, the present data show that M_r drops by about 23%, whereas in the same range, the data of Clemens and Smith,[20] whose experiments were conducted in a Mach 3 flow, show a decrease of nearly 58%. This difference occurs, presumably, because in their experiments the separating boundary layers were laminar, whereas in the present experiments they were turbulent. The difference between the freestream Mach number of the two experiments may also be a factor.

IV. Conclusions

The results of this investigation have shown that the compressible wake of a flat plate consists of large-scale organized motions with embedded vortex structures. The periodicity of these vortex structures is weak as verified by the spectra of static pressure fluctuations and spark schlieren flow visualization. The broadband spectra indicated a distinct frequency, and the Strouhal number based on this frequency was about 0.3. This is in agreement with the previous limited data on flat plate compressible wakes. Such periodic structures have also been noted in free turbulent mixing layers. Both the coherence and periodicity of these structures, however, were found to be Reynolds number dependent, and unlike previous flat plate wake studies, the existence of these vortex structures did not seem to depend on the plate surface roughness. Further study aimed at clarifying this phenomenon is needed.

Analysis of the mean flow characteristics indicated that the wake growth rate is small and that qualitative similarity scaling exists in both the near- and intermediate-wake regions. The virtual origin of the wake was seen to be well upstream of the trailing edge, in agreement with the investigation of Bonnet et al.,[12] but unlike the results of Nakagawa and Dahm,[35] who found that the virtual origin existed downstream of the trailing edge. The relative Mach number distribution in the wake showed that compressibility effects were small.

Acknowledgments

The authors are grateful to R. Bleakley for assistance in conducting the experiments and Luke Janiche for his assistance in preparing figures and photographs. The authors also wish to express their sincere appreciation to the referees for their constructive comments, leading to the improvement of the paper.

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