Interaction of an oscillating vortex with a turbulent boundary layer

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Abstract. An oscillating vortex embedded within a turbulent boundary layer was generated experimentally by forcing a periodic lateral translation of a half-delta wing vortex generator. The objective of the experiment was to investigate the possibility that a natural oscillation, or meander, might be responsible for flattened vortex cores observed in previous work, which could also have contaminated previous turbulence measurements. The effect of this forced oscillation was characterized by comparison of measurements of the mean velocities and Reynolds stresses at two streamwise stations, for cases with and without forcing. The Reynolds stresses, especially $u'w'$, were affected significantly by the forced oscillation, mainly through contributions from the individual production terms, provided the vortex was not too diffuse.

List of symbols

- $a$: amplitude of forced vortex motion
- $f$: frequency of forced vortex generator motion
- $l$: vortex generator root chord
- $L$: flow length scale
- $R_r, R_z$: vortex core radial dimensions in vertical and spanwise directions, respectively
- $R_r$: vortex circulation Reynolds number $R_r = \Gamma / \nu$
- $u, v, w$: instantaneous velocity components in X, Y, Z directions
- $U, V, W$: mean velocities; shorthand notation for $\bar{u}, \bar{v}, \bar{w}$
- $X, Y, Z$: right-hand Cartesian streamwise, vertical, and spanwise coordinate directions
- $\delta$: boundary-layer thickness
- $\Gamma$: overall circulation
- $\nu$: air kinematic viscosity
- $\alpha_x$: streamwise vorticity, $\alpha_x = \partial W / \partial Y - \partial V / \partial Z$
- $\bar{ }_c$: refers to vortex center
- $\bar{ }_c$: maximum value for a particular crossflow plane
- $(\prime)$: (prime) fluctuating component, e.g., $u = U + u'$

1 Introduction

Discrete streamwise vortices are often observed – and employed – in aerodynamic systems which also contain turbulent boundary layers: an example is the use of vortex generators for stall control in diffusers and on airfoils (e.g., Pearcey 1961; McMasters et al. 1985; Stein 1985). Also, streamwise vortices generally appear where secondary flows are created (see Bradshaw 1987, for a review), and can have dramatic effects on wind tunnel flow quality (Morkovin 1979; Mohktari and Bradshaw 1983), skin friction (Spangler and Wells 1964), and heat transfer (Eibeck and Eaton 1985).

The interaction of a relatively weak single vortex with a turbulent boundary layer on a flat plate has served as a prototype for computational (Liandrat et al. 1987) and experimental studies (Shabaka et al. 1985; Westphal et al. 1987). Results from the experiments showed that while the mean flow is only mildly three-dimensional, the distributions of the turbulence quantities were strongly distorted in the presence of the vortex. These effects were magnified with the addition of an adverse pressure gradient. The experimental results also suggested that simple turbulence models cannot yield predictions which are accurate in detail – a conclusion confirmed by the computational work of Liandrat et al., (1987).

The vortex itself was studied by Westphal et al. (1987), who observed core growth and concomitant attenuation of the core peak vorticity as the vortex/boundary-layer interaction progressed downstream. When the core grew to a sufficient fraction of the distance of the vortex center from the surface, flattening of the vortex core shape was observed. The ellipticity attained for similar streamwise positions was greater in the presence of adverse pressure gradient, apparently because of the higher core growth rate. The present study was motivated by this observation of flattened vortex cores. Such flattening, it was believed, might simply be the manifestation of a quasi-steady vortex motion in a plane parallel to the nearby surface. If such a motion occurs, it would also contribute to the measured Reynolds stresses and therefore confound attempts to model the turbulence in calculation methods. It has been suggested that vortices do exhibit a relatively slow natural oscillatory motion; this motion has been termed meander by Bushnell (1983). Some evidence concerning possible vortex meander was cited by Westphal et al. (1987), but doubt remained because the estimated apparent Reynolds stresses due to meander were not large throughout the region of interest compared to typical
measurement uncertainties. Furthermore, the spanwise skin friction distributions measured beneath the vortex for cases very similar to the present experiment (Westphal et al. 1986) showed sharp minima and maxima, again suggesting that the vortex does not meander.

The specific objective of this paper is to examine how meander, if present, alters the distributions of vorticity and Reynolds stresses in the interaction. The approach taken was to simulate the effects of vortex meander by forcing a periodic lateral translation of the vortex generator at a very low frequency. The effects of this oscillation were characterized through comparison of the measured mean velocities and Reynolds stresses at two streamwise stations, for cases with and without forcing. The comparison of the effects of forcing under these two conditions provides additional information concerning vortex meander.

2 Experimental apparatus

The experiments were carried out in the 20 x 80 x 300 cm Boundary-Layer Wind Tunnel of the Fluid Dynamics Research Branch at NASA Ames Research Center. Figure 1 shows a schematic of the test section configuration used, including the location of the vortex generator and the coordinate system. The control wall opposite the test surface was adjusted to maintain constant streamwise pressure in the test section to within 0.5% of the free stream dynamic head. The vortex was generated by a half-delta wing (root chord length, l = 3.8 cm) set at 12° angle-of-attack, with a height of 1.8 cm, and placed at X = 50 cm, which was 30 cm downstream of the boundary-layer trip. The generator height was selected to provide a vortex which would be embedded within the boundary layer (h/δ < 1). The vortex circulation obtained using this generator was about \( \Gamma = 0.13 \) with an inlet free stream velocity of \( U_0 = 22 \) m/s. The resulting vortex Reynolds number \( Rr = \Gamma / \nu \) was approximately 8000.

For the cases with forced vortex motion, a linear spanwise oscillation at 1 cycle per second and a half-amplitude of \( a = 0.5 \) cm was generated using a small DC motor, a gearbox, and a Scotch yoke mechanism. This arrangement allowed for the circulation to remain constant throughout the oscillation cycle, since the generator angle-of-attack was fixed. The oscillation amplitude was selected to be comparable to the unforced vortex radius at X = 150 cm. The reduced frequency of oscillation, based, for example, on the transit time of a particle of free stream fluid in the test section \( (L = 300 \) cm), was quite small: \( fL/U_0 = 0.14 \). Thus, the vortex meander may be considered quasi-steady since the period for one cycle of oscillation is large compared with any flow time scale (note that \( L/\delta = 70 - 300 \) within the region of interaction). Unsteady effects due to airfoil plunging were also not anticipated because of the low frequency of oscillation.

Measurement of all three components of mean velocity and five of the six independent components of the Reynolds stress tensor \( \langle v'w' \rangle \) was not measured) was achieved by using an automated crossed hot-wire anemometer system in which the probe was rolled about its axis to obtain both \( X-Y \) and \( X-Z \) plane measurements (see Westphal and Mehta 1984; Westphal et al. 1986, for more details). For the forced cases, a sufficient averaging time was employed to include 100 cycles of oscillation at each point in a regular rectangular measurement grid of about 150–200 points per plane of data. Results shown include streamwise vorticity contours, which were computed from the measured mean crossflow \( (V \) and \( W \)) velocities by interpolating the data and then evaluating the required derivatives analytically from the interpolation functions. This is the same procedure as used previously by Westphal et al. (1986, 1987).

3 Results

Selected measurements obtained at two stations, \( X = 150 \) cm and \( X = 250 \) cm, are presented and discussed below. Table I gives the experimental parameters at the two measurement stations based on the oscillation amplitude \( a \) and frequency \( f \), and the unforced vortex characteristics: normal position \( Y_c \), radii \( R_\varphi \) and \( R_z \), maximum vorticity \( \omega_{x, \max} \), and circulation \( \Gamma \). The value of \( \delta \) used is for the boundary layer in the absence of the vortex.

<table>
<thead>
<tr>
<th>( X )</th>
<th>( \delta )</th>
<th>( Y_c )</th>
<th>( R_\varphi )</th>
<th>( R_z )</th>
<th>( a/R_\varphi )</th>
<th>( \omega_{x, \max} )</th>
<th>( \Gamma )</th>
<th>( f \delta /U_0 )</th>
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<tr>
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<td>2.1</td>
<td>0.8</td>
<td>1</td>
<td>0.5</td>
<td>0.025</td>
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