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Flow Breakdown for Wings in Ground Effect

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Nomenclature

A_{mom} = momentum area
$\mathit{A\!R}$ = aspect ratio
b = wing span
C_L = lift coefficient
H = wing height above ground
L = wing lift
S = wing area
V = freestream velocity
W_d = downwash velocity
α_d = downwash angle measured from horizontal
ρ = density of air

Introduction

CLASSICAL theory predicts lift should increase as a wing approaches the ground. Wind tunnel tests show the opposite – lift deteriorates sharply at a certain height above the ground. The cause is flow breakdown. The theory of flow breakdown is presented here.

Theory

The momentum area for a wing is given in Ref. 1 as $\pi b^2/4$. From momentum requirements,

$$L = \rho A_{mom} V(2W_d) = C_L \tfrac{1}{2}\rho V^2 S \tag{1}$$

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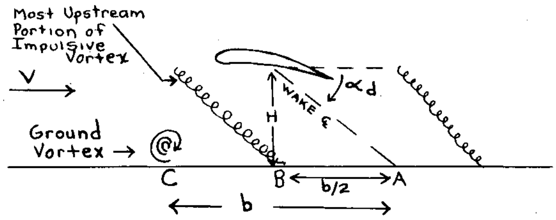

Fig. 1 Side view of impulsive vortex.

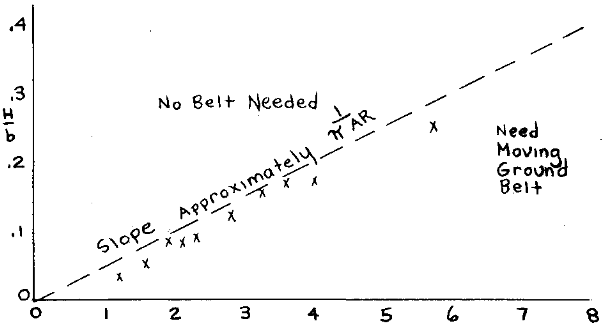

Fig. 2 Turner's graph.

Therefore,

$$A_{mom} = C_L VS/4W_d \tag{2}$$

The classical value of downwash at the wing is

$$W_d = (C_L/\pi \mathit{A\!R})V \tag{3}$$

Combining Eqs. (2) and (3) gives

$$A_{mom} = \pi b^2/4 \tag{4}$$

The wing can be represented with an impulsive vortex of diameter b. The vortex is viewed from the side in Fig. 1.

From classical theory

$$\tan\alpha_d = W_d/V = C_L/\pi \mathit{A\!R} \tag{5}$$

When the upsteam portion of the vortex strikes the ground, it moves to position C, twice the normal distance from the wake centerline. This is proven in Ref. 2. This phenomenon can be understood by noting that were a ring vortex to strike a wall, the velocity through the center would effectively double because it would be encountering an "image" ring coming from the opposite direction. Therefore, for the circulation to remain constant, the diameter of the ring would double.

When the ground vortex is at C, upstream of the wing, it can exert downwash on the wing. This results in flow breakdown. Flow breakdown occurs when

$$\tan\alpha_D = H/b \tag{6}$$

But

$$\tan\alpha_d = W_d/V = C_L/\pi \mathit{A\!R} \tag{7}$$

Equating Eqs. (6) and (7) yields

$$H = bC_L/\pi \mathit{A\!R} \tag{8}$$

Equation (8) shows the height of the wing above the ground at which flow breakdown occurs. Flow breakdown theory correlates well with a number of references. South,[3] using H. Heyson's data,[1] shows for high lift devices that nonmoving ground planes can be used if

$$C_L b/\text{Æ}H<3.3 \tag{9}$$

This is nearly equivalent to the condition just prior to flow breakdown where

$$C_L b/\text{Æ}H<\pi \tag{10}$$

Turner[4] depicts a graph (Fig. 2) showing regions where moving-belt ground planes are needed. The slope of the line depicted on the graph very nearly corresponds to $1/\pi\text{Æ}$. Turner's graph therefore shows flow breakdown occurs when

$$C_L b/\text{Æ}H=\pi \tag{11}$$

This basic flow breakdown concept is applicable to VTOL, STOL, and conventional aircraft if C_L is the total lift coefficient.

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Behavior of a Subsonic Turbulent Slot Jet in Crossflow

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Introduction

THE problem of a round turbulent jet exhausting from a large flat plate into a crossflow has received considerable attention from many investigators (for example, Refs. 1-4). This flat plate problem contains the essential features of the interaction associated with a lifting jet and a freestream flow during the transition of a VTOL aircraft from vertical to horizontal flight. However, in some applications it is desirable to have the jet issuing from a slot (with longer dimension parallel to the freestream) rather than from a round hole. This Note presents some experimental observations on the behavior of such a slot jet.

Apparatus

The jet issued vertically upwards from a flat plate 48 × 66 in. in the chordwise and spanwise directions, respectively, which was mounted 12 in. above the floor of the Georgia Tech 9-ft. wind tunnel.[5] Two different nozzles were mounted in the supply pipe at the center of the plate. One nozzle had a circular exit of 2 in. diam. (round jet); the other nozzle was a slot 1 in. wide, with a 0.5 in. radius at either end (Fig. 1), which was aligned with the longer dimension in the streamwise direction (slot jet). Both exits had the same area. The jet air, which was supplied by a centrifugal compressor, exited at approximately 170°F, allowing the shape of the jet to be determined by means of a thermocouple probe. The probe had a spherical tip 0.04 in. in diameter and was traversed by a remote-controlled actuator. Two other probes were used to measure reference temperatures. One thermocouple probe inserted through the wind tunnel wall was used to measure freestream temperature T_∞, while a second probe in the jet plenum chamber just below the nozzle recorded the jet stagnation temperature T_j. The local temperature T in the jet plume was recorded on an X-Y plotter, while the probe was moved by the actuator in the vertical z direction at a maximum speed of 0.2 in./s. It is recognized that the thermocouple measurements are insensitive if the probe is exposed to jet fluid and crossflow in some intermittent fashion.

Results

Results are presented in terms of contours of constant temperature parameter C_T, where $C_T=(T-T_\infty)/(T_j-T_\infty)$. It is estimated that the values of C_T are in error by less than ±0.02. All of the data were taken at a jet effective velocity ratio (square root of the ratio of the jet dynamic pressure to the freestream dynamic pressure) of $\lambda=8$.

Figure 1 shows pressure and temperature centerlines (where a centerline is defined as a series of maximum points taken from pressure and temperature profiles measured by making vertical surveys along the z axis) for both the circular and slot jets in the plane of symmetry ($y=0$) plotted against distance nondimensionalized by the circular jet diameter, d. The pressure centerline is the locus of points of maximum total pressure, while the temperature centerline is the locus of points of maximum temperature. The pressure centerlines are taken from Mosher,[6] who used the same apparatus; these were spot-checked in the current study. As has been noted elsewhere,[6-8] the slot jet penetrates further into the crossflow than does the circular jet for the same velocity ratio λ. It was observed by Kamotani and Greber[9] that the temperature centerline for the circular jet falls considerably below the pressure centerline. The present data agree with their results taken at $(T_j-T_\infty)=75$°F. Note, however, that the temperature and pressure centerlines almost coincide in the case of the slot jet.

Figure 2 shows the extent and shape of the slot jet in y-z planes perpendicular to the freestream (x) direction at two

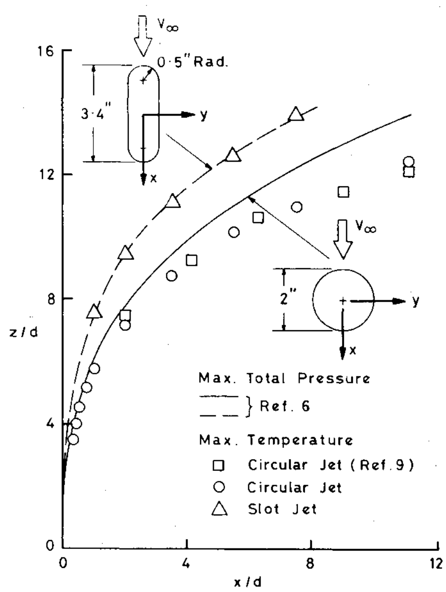

Fig. 1 Pressure and temperature centerlines ($y=0$) circular and slot jet, $\lambda=8$.

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