78-109

Measured Wake-Vortex Characteristics of Aircraft in Ground Effect

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In support of the NASA wake vortex alleviation program, measurements were made of the influences of a ground plane on vortex trajectories and velocity profiles within lift-generated wakes. The wakes were generated by towing 0.61-m (2-ft) span models of a B-747 and DC-10-30 under water in a ship model basin. The models were configured with landing flaps and flight spoilers to investigate the wake characteristics of these aircraft in ground effect at simulated full-scale distances of 19-116 m (62-380 ft) above the ground. The ground plane caused modifications in the vortex trajectories but did not alter vortex interactions and merging patterns in these multiple vortex wakes. Some distortions in vortex vertical (tangential) velocity profiles were recorded as a result of vortex lateral motions and vortex interactions with the viscous boundary layer on the ground plane; however, maximum tangential velocities remained unchanged.

Nomenclature

$\mathcal{R}$	= wing aspect ratio
b	= wing span
b_e	= far-field vortex separation distance
C_L	= lift coefficient
GP	= ground plane
H	= initial height of vortex above ground plane
LDG	= landing configuration
LDG(S)	= landing configuration with spoilers deployed
MAC	= means aerodynamic chord
r	= radial distance from vortex centerline
S	= wing semispan
U_∞	= towing speed
V_z	= vortex vertical (tangential) velocity component
X	= streamwise position, positive downstream of wing tip trailing edge
Y	= spanwise position (from fuselage centerline)
Z	= height above ground plane (of wing leading edge at root chord)
α	= angle of attack
Γ_0	= circulation, $(C_L b U_\infty)/2\mathcal{R}(b_e/b)$
Δ	= unit change
δ	= trailing-edge flap deflection, positive down
ν	= kinematic viscosity

Subscripts

IF	= inboard flap
M	= maximum
OF	= outboard flap

Introduction

RECENT research[1,2] into effective ways for dispersing the concentrated vorticity in lift-generated wakes that trail heavy aircraft, has shown that selective vortex interactions provide a promising technique for reducing this potential hazard. There are typically five vortices, shed from each side of the wing, close behind an aircraft in the landing configuration. The desired vortex interactions in these wakes can be induced by modifying the vortex trajectories with an altered wing span loading and/or injecting secondary vortices[3] or turbulence into the wake. One practical application of this approach is the use of flight spoilers to disperse vorticity in the wake generated by the B-747 airplane.[1,2] The purpose of the ground-based measurements discussed here is to investigate the effect of a ground plane on vortex trajectories, interactions, and velocity profiles in the wakes of B-747 and DC-10-30 models in the landing configuration, with and without flight spoilers deployed.

The experiment was performed in the University of California's ship model basin at Richmond, California. Vortex trajectory information was obtained from photographic records of the dye-marked wakes. Vortex velocity profiles were measured using a scanning laser velocimeter; data were obtained to distances of 106 span lengths behind the models. The models were fitted with leading-edge slats, trailing-edge flaps, removable flight spoilers, and landing gear.

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Experimental Apparatus and Procedure

Facility and Model Description

The University of California's ship model basin is 61 m long, 2.44 m wide, and 1.7 m deep. Models are strut-mounted to an electrically driven carriage and towed through the water past a viewing station (Fig. 1). At this station, large glass windows in the side of the tank allow the model wake to be observed as it ages. All data were obtained at a model towing speed of 1 m/s, which resulted in a mean chord Reynolds number of 82,000. Justification for testing at this low a Reynolds number is discussed in Refs. 2 and 4. Since the wake characteristics of previous tests in this facility and those of higher Reynolds number wind-tunnel and flight tests have been in general agreement,[1,5] it is assumed that the wake-vortex ground effect data obtained in this test should be representative of flight results.

Models of a B-747 and DC-10-30 aircraft (Figs. 2 and 3) were tested in the nominal landing configurations (LDG), and with two flight spoilers deployed on each wing half (LDG(S)). All configurations were tested with landing gear extended. Each model had the trailing edges of the spoilers located along the hinge line of the outboard flap. For the B-747, the spoiler chord was 12% of the MAC; the spoilers were positioned between 0.59 and 0.69 of the semispan. For the DC-10-30, the spoiler chord was 8.5% of the MAC and they were located from 0.51 to 0.61 of the semispan. Table 1 lists the model aspect ratios, lift coefficients, and angles of attack for the

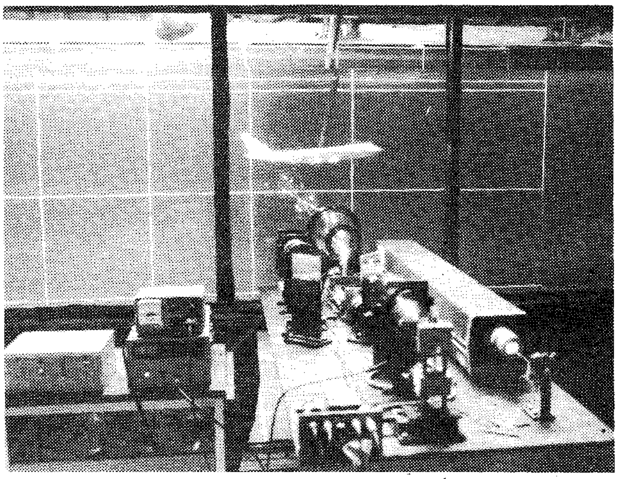

Fig. 1 Test installation photograph.

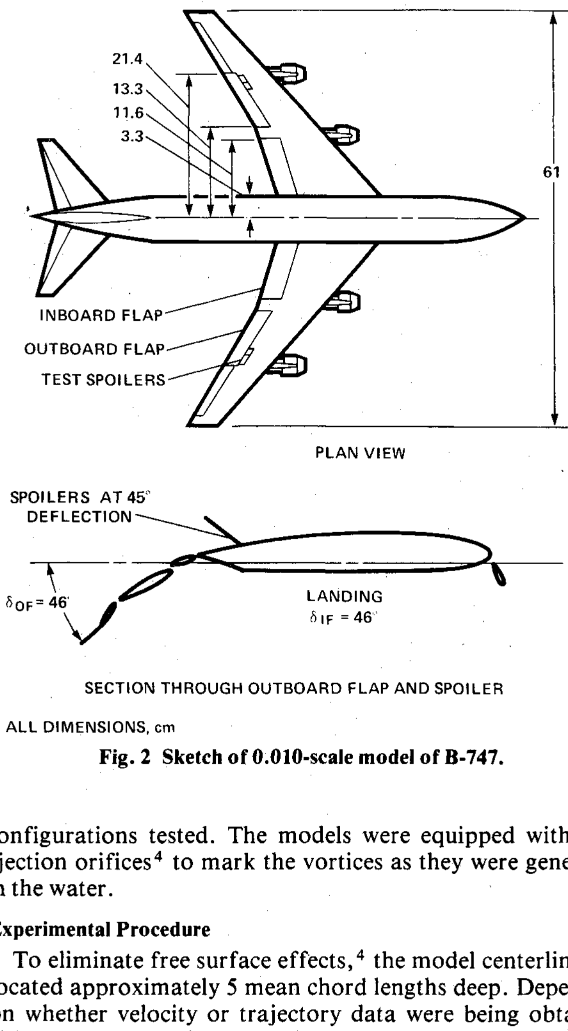

Fig. 2 Sketch of 0.010-scale model of B-747.

configurations tested. The models were equipped with dye-ejection orifices[4] to mark the vortices as they were generated in the water.

Experimental Procedure

To eliminate free surface effects,[4] the model centerline was located approximately 5 mean chord lengths deep. Depending on whether velocity or trajectory data were being obtained, either the scanning laser velocimeter or camera equipment was activated prior to the model's arrival at the viewing station; the timing for a run was initiated as the wing tip trailing edge passed a reference point. For velocity data, the water in the viewing section of the tank was seeded with polystyrene copolymer latex spheres to provide a sufficient number of scattering particles to ensure laser velocimeter signals with adequate strength and resolution. The combination of a small particle size (diameters of 2 to 15 μ) and a specific gravity of 1.06 for these spheres ensures flow-tracing fidelity. The elevation of the velocimeter was set and kept constant during a run, and the aging vortices were allowed to descend through its optical axis. The laser beams were focused at a point (Fig. 1) and this focal point was continually scanned back and forth across a preset portion of the tank to obtain the desired velocity profiles. The focal volume was less than 0.5 mm in diameter, and the smallest vortex core measured was 10 mm in diameter; hence, good vortex velocity profile resolution was achieved. The scanning rate was such that the rate of change of downstream position (age) of the wake with scanning position of the focal point was nominally $\Delta(X/b)/\Delta[Y/(b/2)] \doteq 2$. Typically then, the wake aged about 0.2 s while a vortex core was being scanned. Visual observations and repetition of runs were used as guides for evaluating vortex core penetrations by the focal point.

For trajectory data, cameras were operated at constant frame speeds, allowing vortex age to be determined from the photographic records and towing speed. To eliminate thermal gradients, no underwater lights were used. After each run, the carriage was returned to the starting end of the tank; the velocimeter was then used to monitor water motions to ensure a calm tank prior to the next run (eddy velocities $\leq 0.4\%$ of U_∞). This procedure minimized the effects of vortex meander on the measured vortex trajectories. The calm tank and near-field measurements ($X/b < 106$) also eliminated concern about vortex mutual induction instabilities.

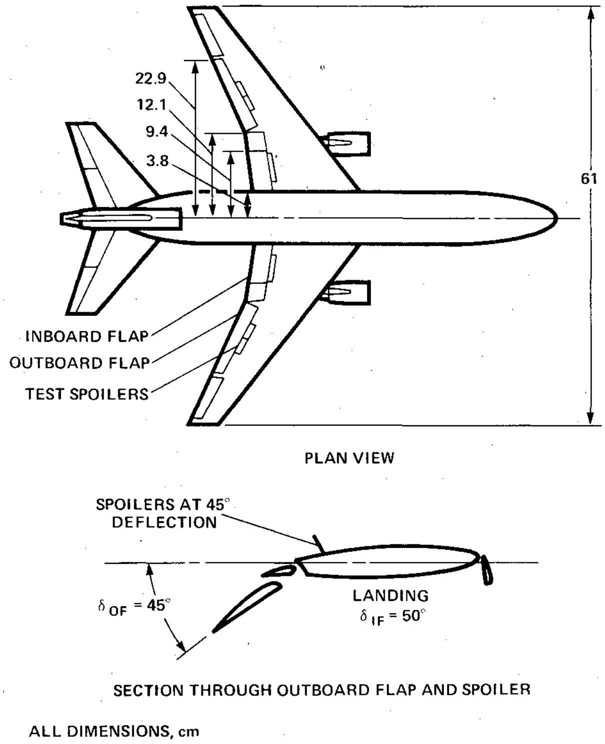

Fig. 3 Sketch of 0.011-scale model of DC-10-30.

Data Acquisition System

Vortex velocity profiles were obtained with a scanning, single-component, argon-ion laser velocimeter (Fig. 1). This instrument is a crossbeam, on-axis, backscatter type, described in detail in Refs. 1 and 6. It uses the bright green color emitted at 5145 Å as its light source. The primary signal-processor was a spectrum analyzer. The signal

Table 1 Model characteristics

Model	Æ	Configuration	C_L	α, deg
B-747	6.96	LDG	1.27	2.9
		LDG(S)	1.35	5.8
DC-10-30	7.5	LDG	1.50	7.0
		LDG(S)	1.36	8.0

frequency at maximum intensity in the power spectrum is directly proportional to the average flow velocity, at that instant in time. When the intensity is greater than a preselected threshold level, a signal sampler permits the frequency to be recorded on magnetic tape. The resulting frequency-time history for each test run is then stored for later processing to a vortex velocity-time history. The time history of the position of the laser beam focal point in the tank is obtained from the output of a potentiometer located on the velocimeter traversing mechanism. A combination of the preceding data yields vortex velocity profiles. To obtain vortex age (or downstream position), a time-code generator was activated as the model passed the viewing station.

Vortex trajectory data were obtained by illuminating a cross section through the wake (a Trefftz plane view) and photographically recording the position of the dye-marked vortices as a function of time. An 800-W xenon arc-lamp with a specially designed lens and light slit system was used to project a thin light sheet through the window and across the tank. Vortex positions determined from the photographs were corrected for both camera viewing and cone angles.

The presence of a ground plane was simulated by placing a 2×2.5m (7×8 ft) table in the tank at the viewing station. The distance between the model and ground plane was varied by changing the table height.

Discussion of Results

Wakes of the B-747 and DC-10-30 models, both in and out of the influence of a ground plane, in the landing (LDG) and landing with spoilers (LDG(S)) configurations will be discussed. Results from the starboard vortex of the dominant vortex pair in the wake (as determined from the flow visualization studies) are presented as: 1) vertical plane vortex trajectories (Figs. 4 and 6-8); 2) vertical (tangential) velocity profiles (Figs. 9-16); and 3) downstream dependence of maximum vertical velocity (Fig. 17).

Vortex Trajectories

Vortex trajectory data were obtained from both the velocimeter measurements and from marking the multiple vortices[7] and photographing them as they interacted within the wake to form the final vortex pair.

B-747 Model

Figure 4 summarizes the trajectory data for the B-747 model in the LDG configuration at heights above the ground plane of 3.80, 1.26, 1.12, and 0.70 semispans. This and subsequent figures relate the spanwise and vertical positions of the prominent starboard vortex. The circulation Reynolds number, Γ_0/ν, was typically 7×10^4. Photographic results are represented as the faired curves and the velocimeter data are shown by symbols. Next to each symbol is listed the corresponding downstream position in span lengths (vortex

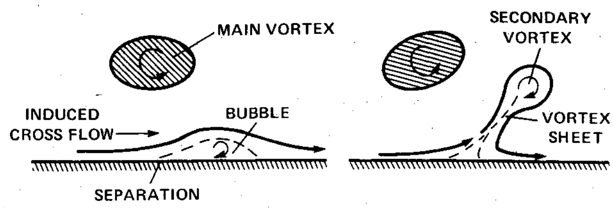

Fig. 5 Sketch of proposed vortex-boundary-layer interaction, from Harvey and Perry[9]: a) section downstream of initial separation, b) subsequent development of secondary vortex.

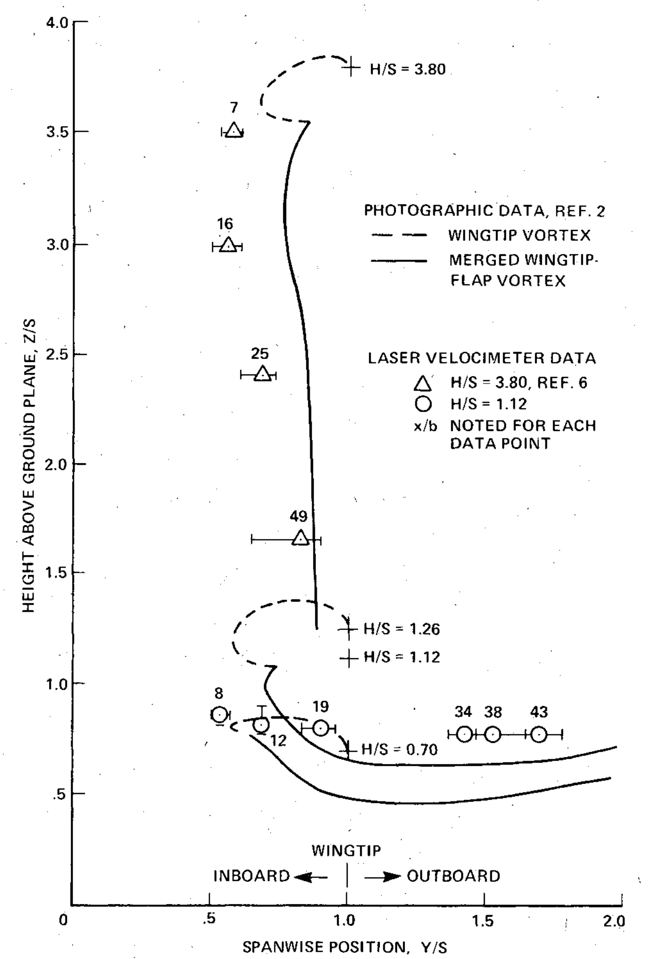

Fig. 4 Vortex trajectory data: B-747 LDG configuration, starboard side, $\Gamma_0/\nu\simeq7\times10^4$.

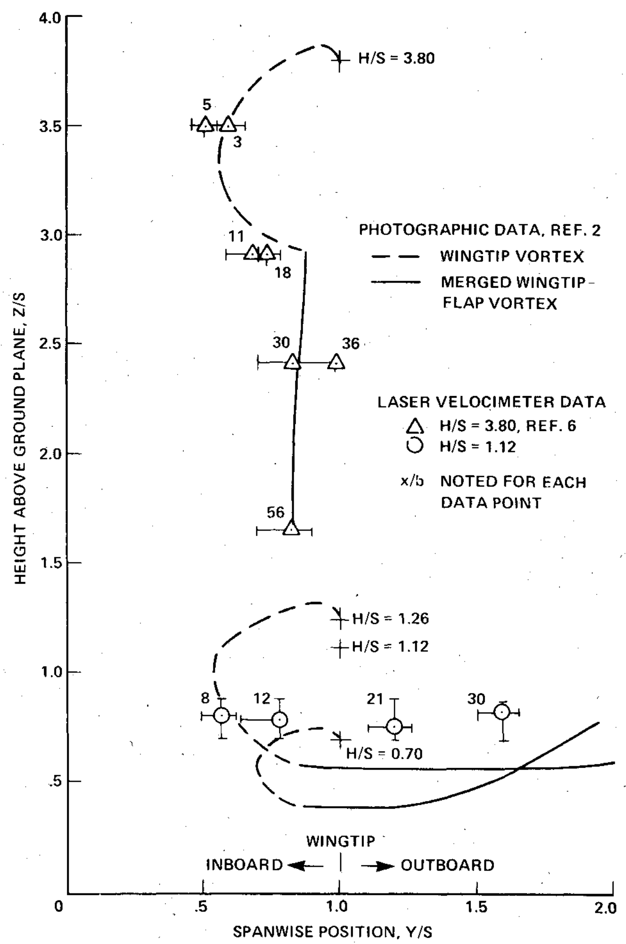

Fig. 6 Vortex trajectory data: B-747 LDG(S) configuration, starboard side, $\Gamma_0/\nu\simeq7\times10^4$.

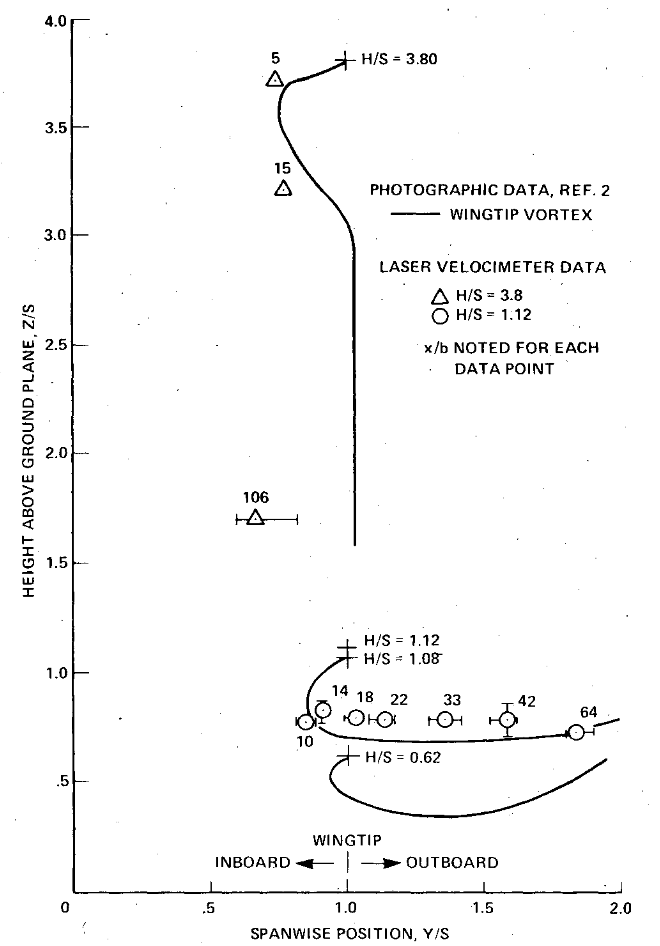

Fig. 7 Vortex trajectory data: DC-10-30 LDG configuration, starboard side, $\Gamma_0/\nu \simeq 7\times10^4$.

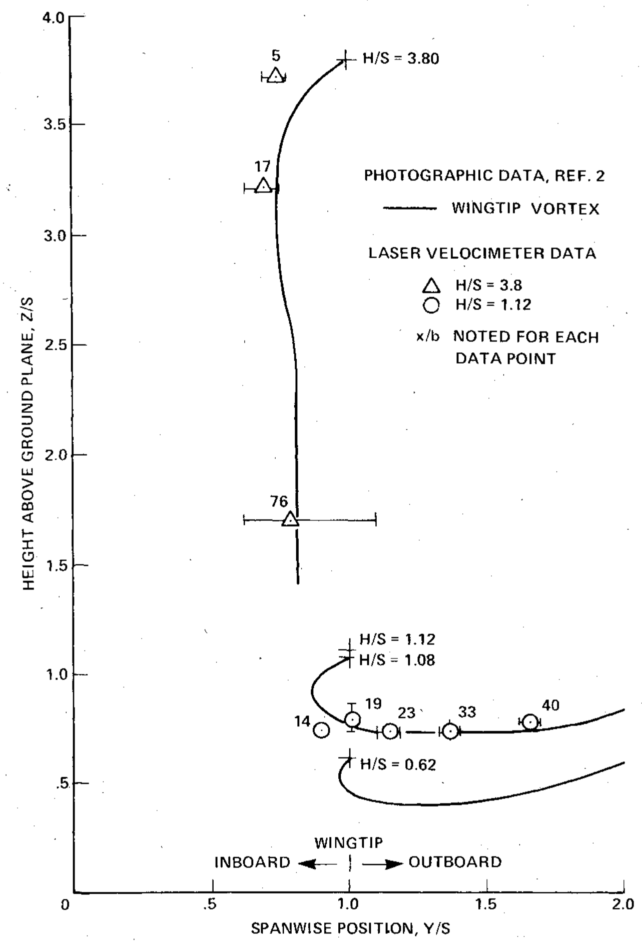

Fig. 8 Vortex trajectory data: DC-10-30 LDG(S) configuration, starboard side, $\Gamma_0/\nu \simeq 7\times10^4$.

age). In the LDG configuration, the B-747 sheds five vortices from each side of the wing. Four of these vortices are due to the span-loading gradients caused by the flaps; the fifth is due to the span-load gradient at the wing tip. The dominant and most persistent vortex is shed from the outboard edge of the outboard flap. The wing tip vortex moves inboard and merges with it. The remaining flap vortices interact with each other and with the vortex from the tip of the horizontal stabilizer to form a region of diffused vorticity at and below the aircraft centerline.[4]

The photographic data shown in Fig. 4 represent a composite of the wing tip vortex trajectory initially (dashed line), and then the dominant flap vortex trajectory after merger (solid line). As expected from potential flow theory, the vortices descend toward the ground plane and then begin a horizontal motion in the outboard direction. This characteristic motion is due to the vortices interacting with their "mirror" images. As the initial distance between the model and the ground plane was reduced (decreasing H/S) the vortices were observed to descend more slowly and move closer to the ground plane before moving parallel to it. This result was also seen in the experimental findings of Barker and Crow.[8] Consequently, in this LDG configuration, as the model height above the table was decreased, the wing tip vortex appeared to move further inboard and merged with the flap vortex at a more inboard position.

It is hypothesized that the rise of the vortex after some lateral outboard movement at a constant height above the ground plane, is due to a viscous interaction between the vortex and an induced boundary layer on the ground plane below (i.e., Fig. 5). This effect has previously been seen in flight measurements,[9] in other ground-based experiments,[8,10] and more recently in the viscous flow calculations of Bilanin et al.[11] Total head surveys by Harvey and Perry[10]—of the flowfield behind a semispan rectangular wing—suggest that this vortex "bounce" is a result of the following sequence of events: 1) the vortex induces a crossflow on the ground plane below it; 2) since viscous shear reduces the total head, the boundary layer resulting from the induced crossflow must negotiate an adverse pressure gradient as it passes under the vortex; 3) when the vortex is sufficiently near the ground, the pressure gradient is strong enough for separation to occur, and a bubble forms, containing vorticity of opposite sense to the main or generating vortex (Fig. 5a); 4) as the wake ages, this bubble grows and detaches from the floor as a secondary vortex fed by a vortex sheet from the separation point (Fig. 5b); and 5) the secondary vortex induces an upwash that causes the main vortex to rise. Depending on the model configuration, subsequent trajectory figures all display this viscous interaction to a lesser or greater extent. In all cases, the closer the model was to the ground plane (lower values of H/S), the sooner the vortex began to rise up from or "bounce" off it, and the greater the rate at which it rose. A similar finding was reported by Barker and Crow,[8] who suggest that the vortex rebounding may be the effect of the finite vortex core radius. Their water tank data indicate a vortex bounce from free surfaces as well as solid ground planes. Deformation of the vortex core as it interacts with an image plane could explain the rebounding as well as the period of oscillation evident in their "apparent circulation" time histories. However, the numerical calculations of Bilanin et al.[11] show that the vortex "bounce" phenomenon does not occur unless a viscous boundary condition is applied, even though the vortex cores are of finite size. In addition, they

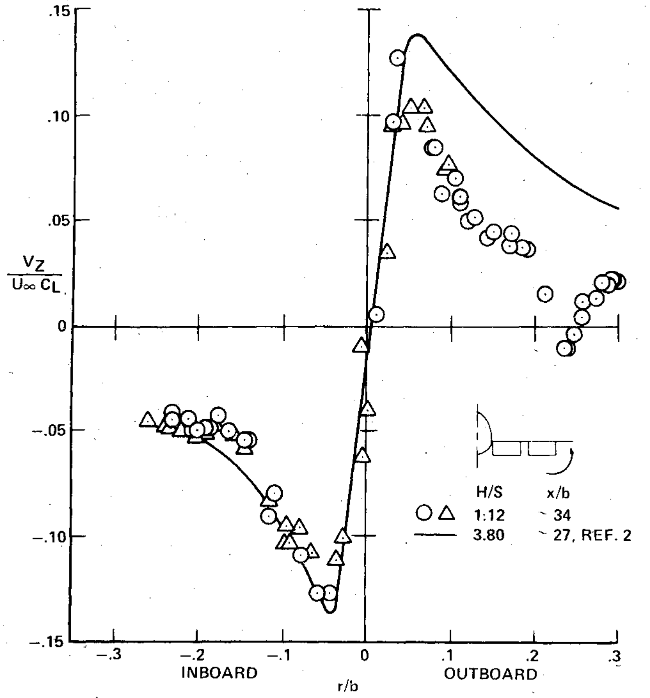

Fig. 9 Effect of ground plane on dominant flap vortex vertical velocity profile: B-747 LDG configuration, starboard side.

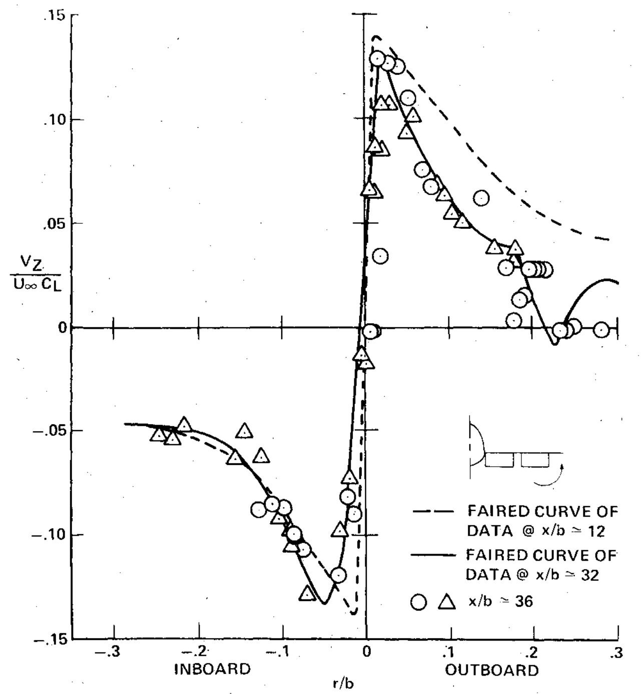

Fig. 11 Effect of downstream distance on dominant flap vortex vertical velocity profile in the presence of a ground plane: B-747 LDG configuration, starboard side, $H/S = 1.12$.

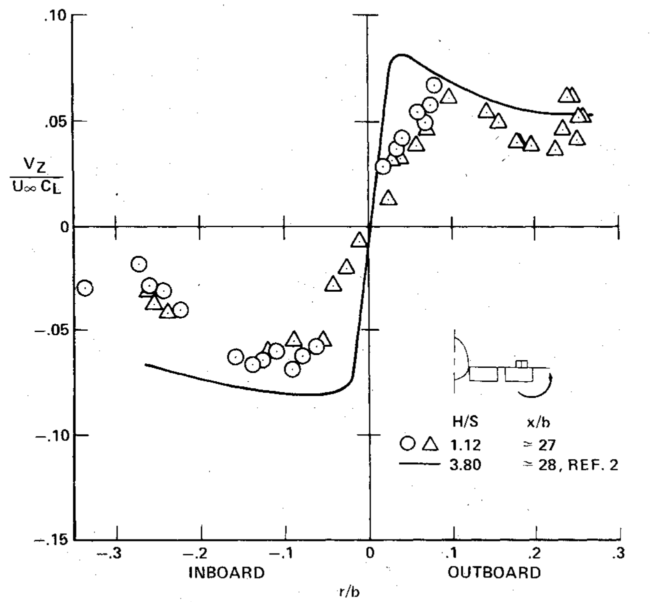

Fig. 10 Effect of ground plane on dominant flap vortex vertical velocity profile: B-747 LDG(S) configuration, starboard side.

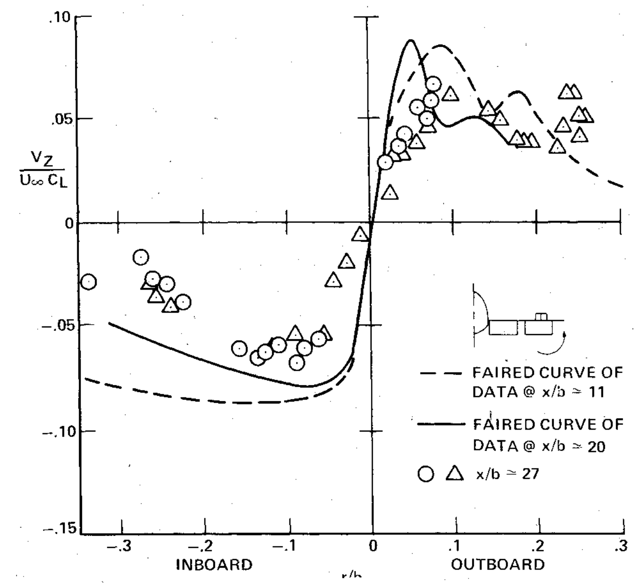

Fig. 12 Effect of downstream distance on dominant flap vortex vertical velocity profile in the presence of a ground plane: B-747 LDG(S) configuration, starboard side, $H/S = 1.12$.

show a weak dependence of this phenomenon on circulation Reynolds number, which is consistent with the similarity between observations of flight data and low Reynolds number ground-based measurements.

Shown in Fig. 6 is the trajectory data for the B-747 model in the LDG(S) configuration. With spoilers deployed, the merging of the wing tip vortex with the flap vortex is delayed and occurs closer to the ground plane. At $H/S = 0.70$, merging was actually delayed until the vortices were engaged in viscous interactions with the ground plane boundary layer and the resulting wake appeared to be quite chaotic and diffuse. In general, the wakes of the LDG(S) configuration looked more disorganized and diffused than those of the LDG configuration. Although the presence of the ground plane modified the vortex trajectories of both the B-747 LDG and LDG(S) wakes, it did not alter the eventual vortex interactions and merging.

DC-10-30 Model

Figures 7 and 8 present vortex trajectory data for the DC-10-30 model in the LDG and LDG(S) configurations, respectively. Of the five vortices shed from each side of the wing, the dominant and most persistent vortex is that from the wing tip. This vortex interacts with the vortex from the outboard side of the outboard flap but does not merge with it. The wakes of these two configurations are basically the same, with the exception that there is less interaction between the flap and wing tip vortices in the LDG(S) configuration.

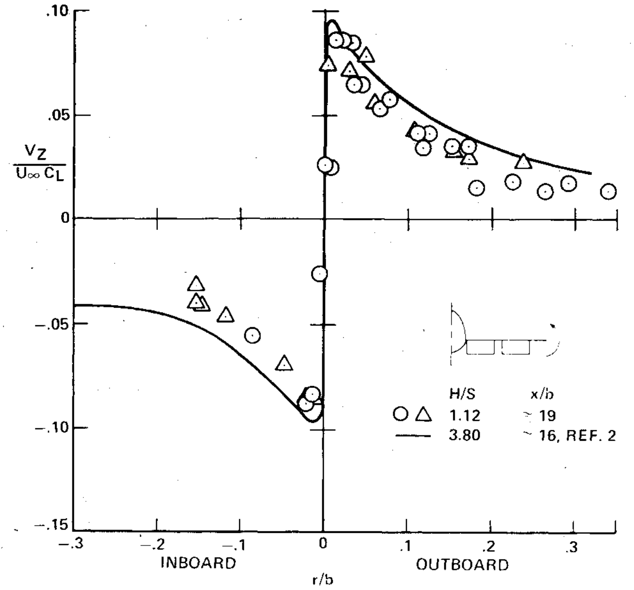

Fig. 13 Effect of ground plane on wing tip vortex vertical velocity profile: DC-10-30 LDG configuration, starboard side.

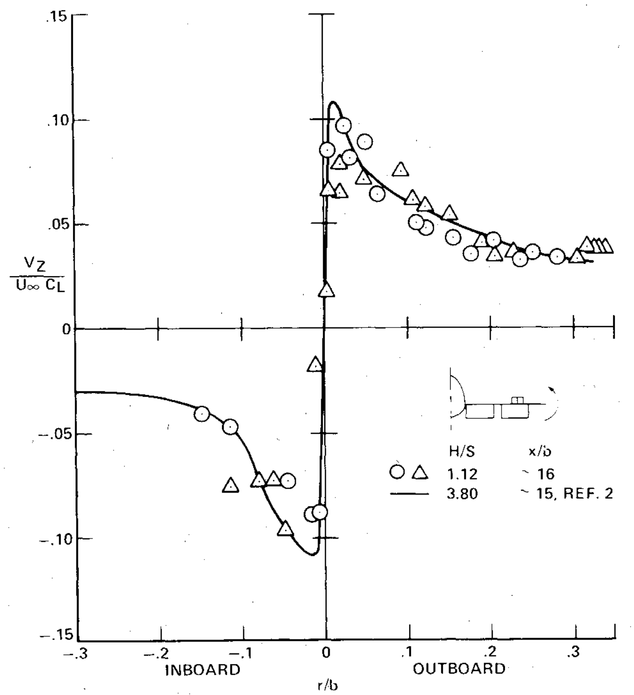

Fig. 14 Effect on ground plane on wing tip vortex vertical velocity profile: DC-10-30 LDG(S) configuration, starboard side.

Vortex Vertical Velocity Profiles

The laser velocimeter was used to selectively and spatially scan the dye-marked wake vortices and to measure their vertical (tangential) velocity profiles.

B-747 Model

Figure 9 shows the effect of a ground plane on the velocity profile of the dominant flap vortex in the wake of the B-747 LDG configuration at a downstream distance of approximately 30 span lengths. At this downstream position, the data in Fig. 4 suggest that the vortex corresponding to $H/S = 3.80$ is moving vertically downward, while the vortex with $H/S = 1.12$ is moving laterally outboard under the influence of the ground plane. It is on the outboard side of the vortex velocity profiles of Fig. 9 that differences are evident. The positive velocity gradient, which appears at $r/b = 0.25$ for the vortex close to the ground plane, is believed to be the inboard portion of the secondary vortex that has been generated with opposite sign (see Fig. 5b). The proximity of these two regions of opposite sign vorticity causes a deformation of the main vortex. These results are in agreement with the theoretical predictions of Bilanin et al.[11] Although the interaction with the ground plane has not lowered the maximum vertical velocity at this downstream location, the deformation of the velocity profile has resulted in a reduced area under the curve. This effect suggests a lowered induced rolling moment on an encountering lifting surface.

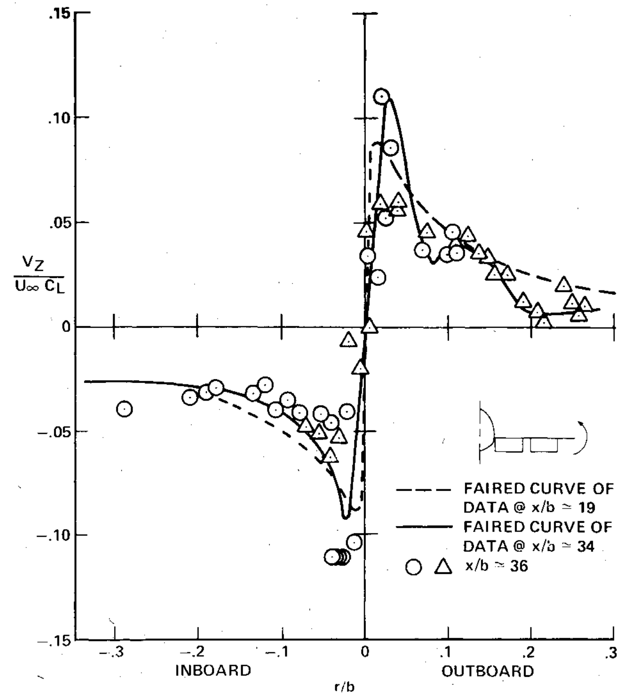

Fig. 15 Effect of downstream distance on wing tip vortex vertical velocity profile in the presence of a ground plane: DC-10-30 LDG configuration, starboard side, $H/S = 1.12$.

Figure 10 presents a similar comparison for the B-747 LDG(S) configuration. Once again, the velocity profile reflects the presence of a secondary vortex of opposite sign. Although the maximum vertical velocities are comparable, the vortex closest to the ground plane ($H/S = 1.12$) appears to have a reduced velocity gradient.

The effect of downstream distance on the vertical velocity profile of the dominant flap vortex, in the presence of the ground plane ($H/S = 1.12$), is shown in Figs. 11 and 12 for the B-747 in the LDG and LDG(S) configurations, respectively. In Fig. 11, the effects of the viscous interaction of the vortex and the ground plane are not distinguishable at 12 span lengths downstream, but they are at 32 and 36 span lengths. In Fig. 12, the saddle shape of the outboard side of the velocity profile in the LDG(S) configuration at 11 and 20 span lengths is believed to be a consequence of the spoiler-induced delay in the merger of the wing tip vortex and the flap vortex.[6] However, by 27 span lengths downstream, a portion of the ground plane secondary vortex is evident at $r/b \simeq 0.225$.

DC-10-30 Model

Figures 13 and 14 compare the effect of the ground plane on the vertical velocity profile of the dominant wing tip vortex in the wake of the DC-10-30 LDG and LDG(S) configurations. Comparisons are made with the only available data[2] and are limited to downstream distances of 15 to 19 span lengths. The trajectory information of Figs. 7 and 8 indicates that at these downstream locations, the $H/S = 1.12$ vortex is just beginning its outboard lateral movement along the ground plane. No significant differences are apparent in

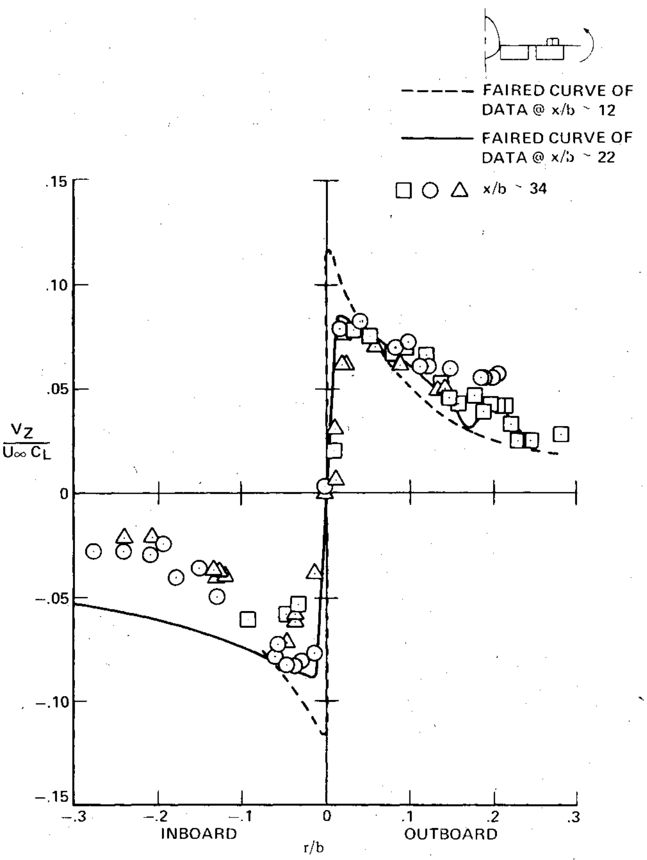

Fig. 16 Effect of downstream distance on wing tip vortex vertical velocity profile in the presence of a ground plane: DC-10-30 LDG(S) configuration, starboard side, $H/S = 1.12$.

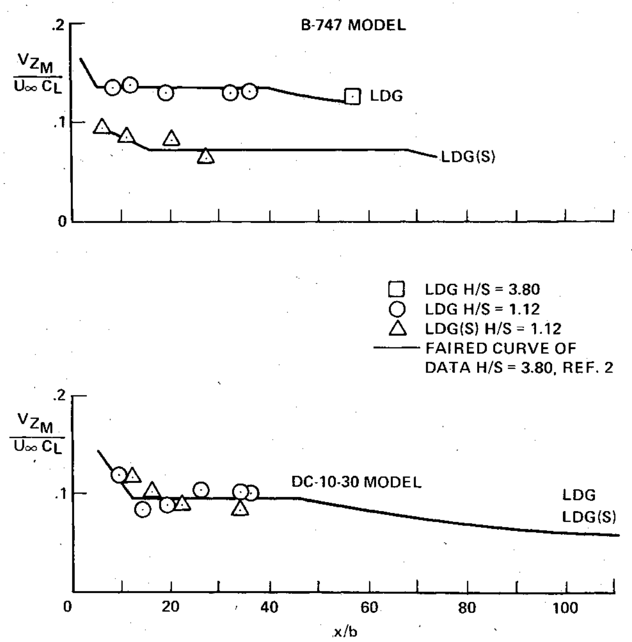

Fig. 17 Effects of downstream distance and ground plane on dominant vortex maximum vertical velocity.

the velocity profiles of either of the configurations at these downstream distances. However, at $x/b = 34$ (Fig. 15), the outboard side of the velocity profile shows deformation, and a secondary, opposite sign vortex at $r/b \simeq 0.175$. A portion of the ground plane secondary vortex is also apparent (as early as 22 span lengths) in the LDG(S) data of Fig. 16.

Vortex Maximum Tangential Velocity

The effects of spoilers, ground plane, and downstream distance on vortex maximum vertical velocity are summarized in Fig. 17 for the B-747 and DC-10-30 models. Maximum velocity is defined as the average value of inboard and outboard peak vertical velocity from a given velocity profile. The now familiar "plateau"[12] in maximum velocity is readily identifiable. There is a 44% reduction in velocity as a result of deploying spoilers on the B-747 model. Comparable reductions in induced rolling moments measured on lifting surfaces encountering these wakes have been reported by Croom[13] and others.[1,14] Although the presence of the ground plane was seen to modify the vertical velocity profiles and to introduce secondary vortices of opposite sign, there was no apparent reduction in maximum velocity when the vortex was moved from $H/S = 3.80$ to $H/S = 1.12$. Data could not be obtained at downstream distances beyond 36 span lengths at $H/S = 1.12$ due to vortex instabilities induced by the upstream edge of the ground plane as the descending vortices approached it.

Summary of Results

Vortex trajectory and velocity measurements were made in the lift-generated wakes of B-747 and DC-10-30 models to provide details of vortex behavior in ground effect. The models were tested in their landing configurations with and without flight spoilers deployed. A summary of the results of these measurements, which simulate full-scale distances above the ground of 19-116 m, include the following:

1) The ground plane caused modifications in the vortex trajectories but did not alter vortex interactions or merging patterns in these multiple-vortex wakes.

2) When the distance between model and ground plane was reduced (decreasing H/S), the vortices appeared to descend more slowly and to move closer to the ground plane before moving laterally outboard.

3) While there is some conjecture as to what eventually causes a vortex to move up away from a ground plane (in the absence of wall effects), that is, a viscous interaction or a finite core radius, the results of this test seem to support the idea that an interaction between descending vortex and induced viscous boundary layer on the ground plane below it, causes a secondary vortex of opposite sign to form outboard of the main vortex. The mutually induced upwash of these vortices causes the main vortex to subsequently rise up away from, or "bounce" off the ground plane. This "bounce" appeared to occur sooner and was more pronounced when the model passed closer to the ground plane and when the model spoilers were deployed.

4) Although the interaction with the ground plane did not lower vortex maximum vertical velocities, deformations of the velocity profile due to vorticity gradients at the secondary vortex interface resulted in a reduced area under the main vortex velocity profile. This, in turn, suggests a lowered induced rolling moment on an encountering lifting surface due to the presence of the ground plane.

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