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Full-Scale Wake Flow Measurements with a Mobile Laser Doppler Velocimeter

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Wake flow measurements were conducted with a mobile Laser Doppler Velocimeter (LDV). The measurements included surveys of aircraft wake vortices behind a B-747 aircraft, aircraft carrier wake measurements from aboard the U.S.S. Nimitz, and tower wake measurements for a 100-kW wind turbine. Results of these tests demonstrated that a mobile ground-based LDV is a versatile and useful tool for the measurement of full-scale three-dimensional wake flows. The potential is demonstrated for utilization of this system to study complex wakes for a variety of applications.

Introduction

SURVEYS of wake flows have been traditionally hampered by probe interference, probe alignment, and lack of scan capability for measuring the spatial and temporal variation in the velocity field. A mobile Laser Doppler Velocimeter (LDV) was developed for tracking aircraft wake vortices and measuring winds aloft.[1-5] Recently, this system was applied to measure the details of wake flows associated with aircraft during low-altitude flybys, the wake aft of an aircraft carrier, and the wake behind a wind turbine.

LDV Principle of Operation

An LDV remote sensor involves the measurement of the Doppler frequency shift of a laser radiation backscattered by the atmospheric aerosol. The instrument incorporates means to transmit the laser radiation to the region of interest, collect the radiation scattered from the atmospheric aerosol, and to photomix on a photodetector the scattered radiation and a portion of the transmitted beam. The difference between the transmitted frequency and the returned frequency is the Doppler shift frequency. The Doppler frequency shift signal is generated at the photodetector and is directly proportional to the magnitude of the velocity component in the direction of the line of sight of the laser beam. This velocity component is referred to as the line-of-sight velocity. The magnitude of the Doppler shift, Δf is given by

$$\Delta f = (2/\lambda)\, |\bar{V}| \cos\theta \qquad (1)$$

where

$\bar{V}$ = the velocity vector in the region being sensed
θ = the angle subtended by the velocity vector and the optic system line of sight
λ = the laser radiation wavelength (10.6μm for CO_2 laser)

A Doppler shift of 188 kHz results per meter per second of line-of-sight velocity component. Measurement of the Doppler shift frequency Δf yields directly the line-of-sight velocity component $|\bar{V}| \cos\theta$. Typical advantages of the laser method are 1) the Doppler shift is a direct absolute measure of the line-of-sight velocity (e.g., a hot wire yields wind speed via a cooling effect on the wire); 2) the ease with which the sensing volume can be varied (only optics pointing and focusing operations being involved); 3) the ambient aerosol provides sufficient scattering, thus enabling operation in "clear air" conditions; 4) the ambient aerosol tracer has a small inertia and responds quickly to variations in airspeed and thus can be a good turbulence indicator; and 5) from the intensity of the backscattered laser radiation the relative particulate concentration can be determined.

The basic component configuration of an LDV system is shown in Fig. 1. The system depends on focusing the transmitter telescope at the location of interest to control the range at which the measurements are taken.

A horizontally polarized, 20W, continuous wave CO_2 laser beam (10.6-μm wavelength) emerges from the laser and is deflected 90 deg by a mirror and a 90% reflecting beamsplitter. The approximately 6-mm-diam beam then passes through a Brewster window and a CdS quarter waveplate which converts the beam to circular polarization. The beam impinges on the secondary mirror and is expanded and

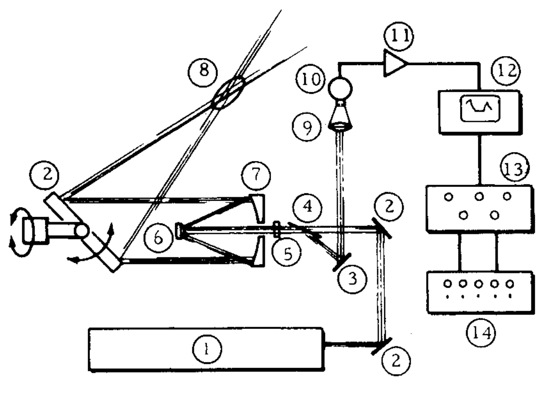

Fig. 1 Typical component configuration of an LDV.

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Index categories: Testing, Flight and Ground; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Lasers.

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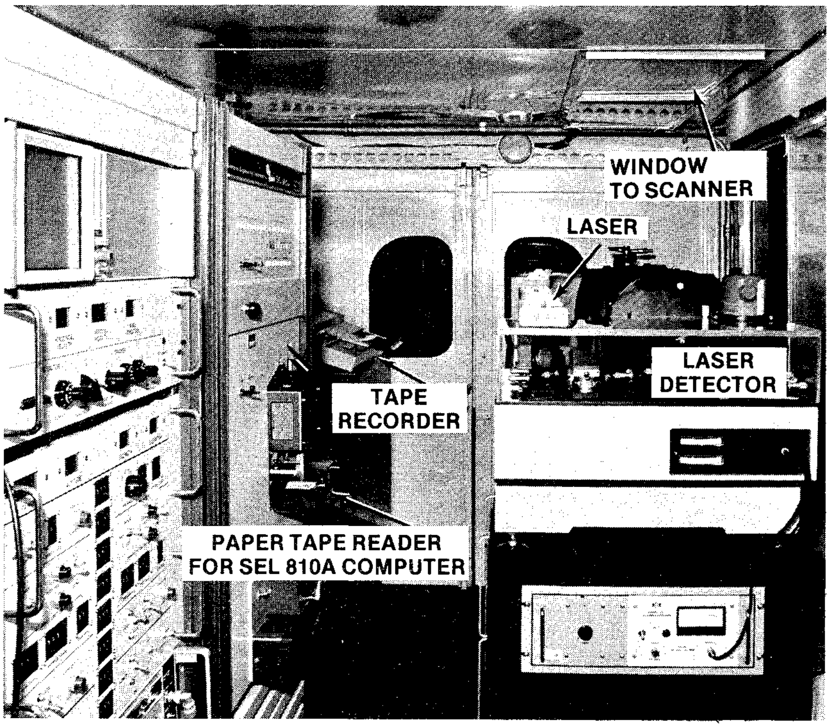


Fig. 2 Interior view of LDV van.

reflected into the primary mirror (30-cm diam) and focused into the atmosphere. A small portion of the outgoing beam is reflected off the secondary mirror back into the interferometer and is used as the local oscillator beam. Energy scattered by aerosols at the focal volume is collected by the primary mirror, collimated by the secondary, and passed through the quarter waveplate. The quarter waveplate changes the polarization of the backscattered radiation from circular to vertical linear polarization. The vertically polarized beam is approximately 78% reflected off the Brewster window and directed to the detector and combined with the local oscillator radiation. After passing through the collecting lens, the returned and the local oscillator beams are photomixed on the detector in a heterodyne configuration. The electrical output of the detector is amplified with a 5-MHz bandwidth, 20-dB gain, low-noise-type preamplifier and fed into a spectrum analyzer. The spectrum analyzer displays Doppler frequency (abscissa) vs returned signal strength (ordinate). A frequency tracker determines the location of the Doppler peak and converts the spectrum analyzer output into a direct velocity readout. A minicomputer accepts data from the frequency tracker and records either the full spectrum or tracked velocity spectrum on digital magnetic tape along with other scan information and parameter values.

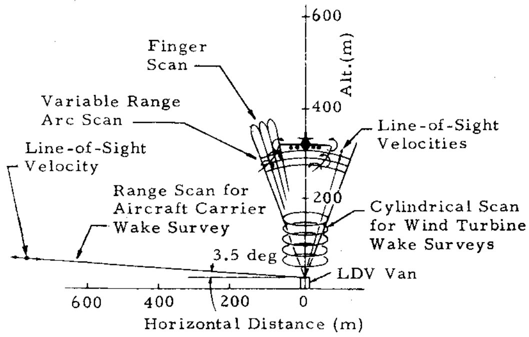


Fig. 3 Multimode scan configurations for LDV measurements.

LDV System Hardware

The LDV hardware is housed in a mobile step van. An interior view of the system is shown in Fig. 2. The laser is shown on the right side with beam output capability through the roof on the right side of the van. The electronics for scan control, spectrum analysis, and tracking and display are shown in the rack closest to the front. The digital tape recorder and paper tape reader and punch for the onboard minicomputer are shown in the rear. The mainframe of the computer is not pictured.

The wake flow measurement applications typically require range, azimuth, and elevation scan capability. The overall scan capability of the LDV is depicted in Fig. 3. The measurement of aircraft wakes with the ground-based LDV was accomplished with a scan pattern coordinating both range and elevation angle including a finger scan and a variable range arc scan. A range scan at discrete elevation angles was utilized for velocity measurements in the wake of an aircraft carrier along the aircraft glideslope. The velocity deficit in the wake of the support tower of a wind turbine was obtained with a cylindrical scan pattern at different altitudes.

Aircraft Wake Measurements

The capability of obtaining the trajectories of aircraft wake vortices with a ground-based LDV system is well established.[3-5] Wake vortex measurements obtained with the LDV at Rosamond, Calif.[6-8] illustrate the ability of a mobile LDV system to determine detailed wake characteristics including vortex rollup, transport, and decay parameters. The objective of the LDV measurements at Rosamond was to determine the influence of vortex alleviation techniques (differential spoiler and flap deployment) and aircraft configurations (flight path angle, landing gear deployment, and height above ground) on vortex transport and decay. The results of the Rosamond wake study demonstrate the strengths and limitations of the LDV ground-based remote sensing technique for aircraft wake studies.

A B-747 aircraft made 54 low-level passes ranging from 38- to 244-m altitude above the LDV van during the Rosamond tests as shown in Fig. 4. Initially, the LDV was located directly under the flight path and scanned arcs in a plane perpendicular to the flight path (Fig. 3) with a complete scan every 2 s. Scans were at a fixed range until the vortex passed through the arc scan, at which time the sensor range was lowered and remained fixed again until the vortex descended

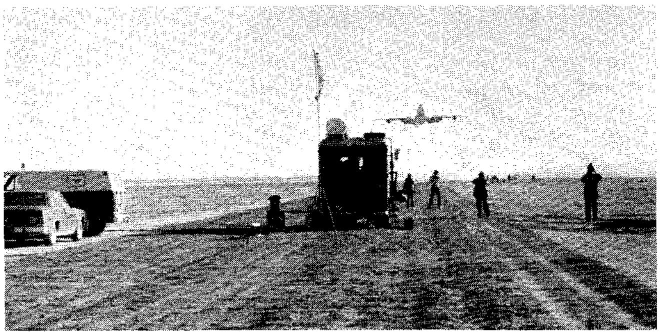


Fig. 4 Lockheed LDV system monitoring wake vortices generated by a B-747 aircraft at Rosamond, Calif. test site.

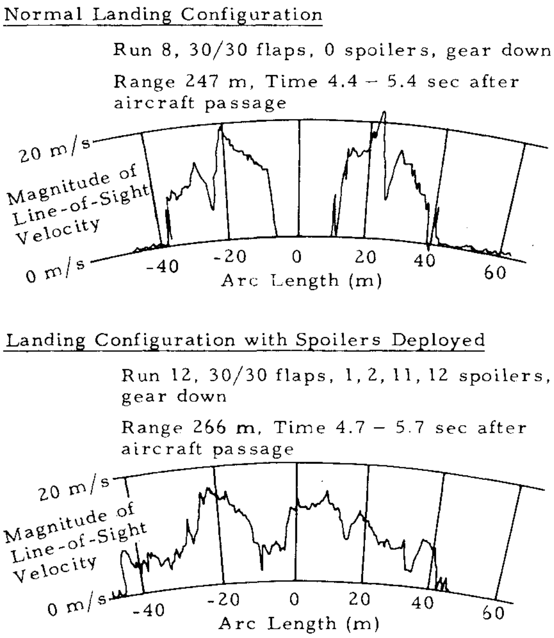


Fig. 5 Magnitude of line-of-sight velocity vs arc length observed during LDV arc scan of B-747 wake.

through the new range. The objective of the overhead arc scan measurements was the measurement of the initial downwash field and the wake vortex rollup process.

A sample of the LDV wake measurements obtained in the arc scan mode is presented in Fig. 5. The double peak signature in the line-of-sight velocity distribution as a function of lateral distance (arc length) indicates the induced velocity field of the trailing vortices. For the B-747 in the normal landing configuration, the vortex lateral spacing is approximately 50 m and the peak rotational velocity is approximately 23 m/s. The double peak signature is considerably broader, less coherent, and lower in magnitude for the flight configuration with the spoilers deployed. An increase in the core radius and turbulence level of the vortex is noted for the flight configuration where the two outer spoilers near each wingtip (spoilers 1, 2, 11, and 12) are deployed. From the distribution of the line-of-sight velocity, or essentially the vertical velocity component, the details of the aircraft near wake are evident including the location, separation, core radius, and rotational velocity of the trailing vortices.

During the second half of the wake study at Rosamond, the LDV was located 60 m from the flight path and scanned simultaneously in elevation and range (finger scan mode) at a frequency of 0.2 and 2 to 2.5 Hz, respectively (Fig. 6). The objective of the finger scan measurements was to track the location of the vortex pair and to observe the vortex decay rates. The finger scan range and elevation settings were

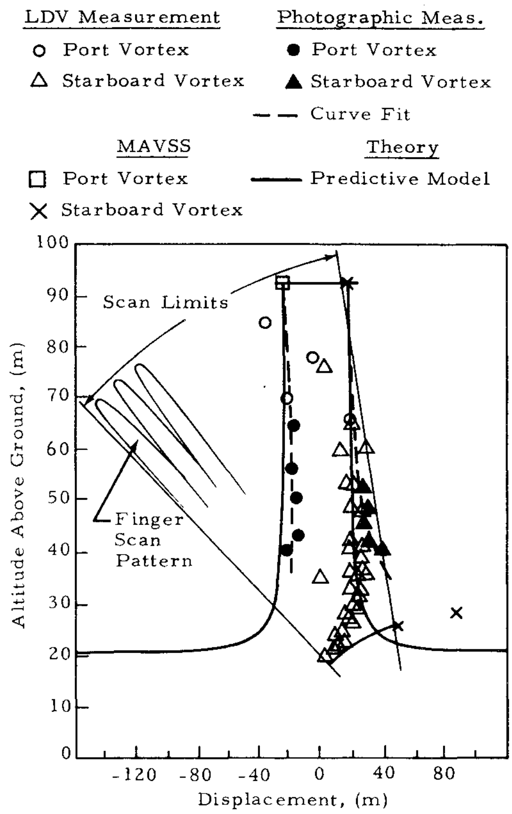


Fig. 6 Wake vortex altitude vs lateral displacement.

selected so that one or more of the trailing vortices would remain in the field of view for extended periods and one or more "cuts" would be made through the vortex core during each elevation scan.

The measurements obtained with the LDV system in the finger scan mode have been used to determine the location of the center of the trailing vortices. A vortex tracking algorithm was used which identified the vortex position from the region of maximum signal intensity (Ref. 5). The vortex descent trajectory observed in the aircraft wake is illustrated in Figs. 6 and 7 for a sample case. The LDV wake vortex measurements are shown along with photographic, monostatic acoustic sensor (MAVSS) and predicted vortex tracks. The predicted trajectories were generated from a theoretical model[9] for a circulation strength $\Gamma = 662\text{m}^2/\text{s}$ and an initial vortex spacing of $b' = 41.8$m and assuming no crosswinds. The vortex tracks measured by the LDV system show a gradual descent of the wake with little lateral motion, trends which are in general agreement with the vortex motion determined photographically and predicted theoretically.

The tangential velocity distribution of the trailing vortex was obtained whenever the finger scan pattern intersected the core of the trailing vortex. The observed line-of-sight velocity distribution, similar to the sample cases shown earlier in Fig. 5, was derectified using the minimum velocity point as the axis of symmetry. A sample of the vortex velocity distribution processed from the LDV finger scan surveys is presented in Fig. 8. From the observed velocity distribution, the core radius, peak tangential velocity, and circulation strength of the trailing vortex were determined as a function of time.

The circulation time history of the wake vortex is illustrated in Fig. 9 for a sample case. The circulation was determined from the average moment of the line-of-sight velocity components within a correlation radius of the computed vortex center (see Figs. 6 and 7). The LDV measurements indicate a relatively constant circulation 20 to 40 s after aircraft passage (approximately 23 to 46 scans downstream) followed by a t^{-1} type decay. For reference, the bound circulation of the wing computed from aircraft lift coefficient

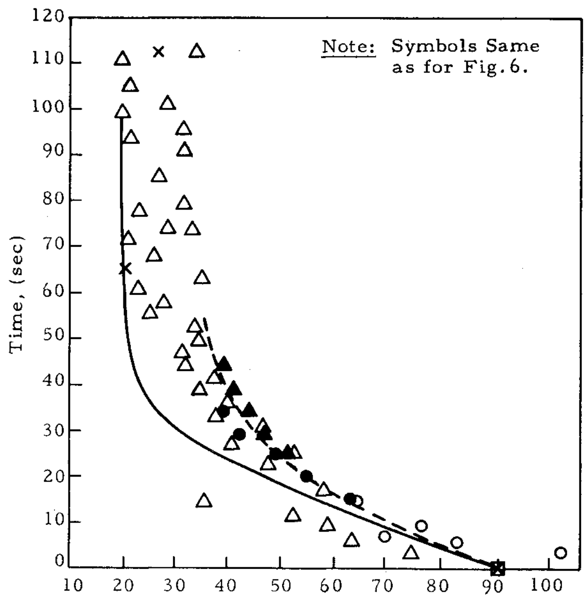


Fig. 7 Wake vortex altitude as a function of time.

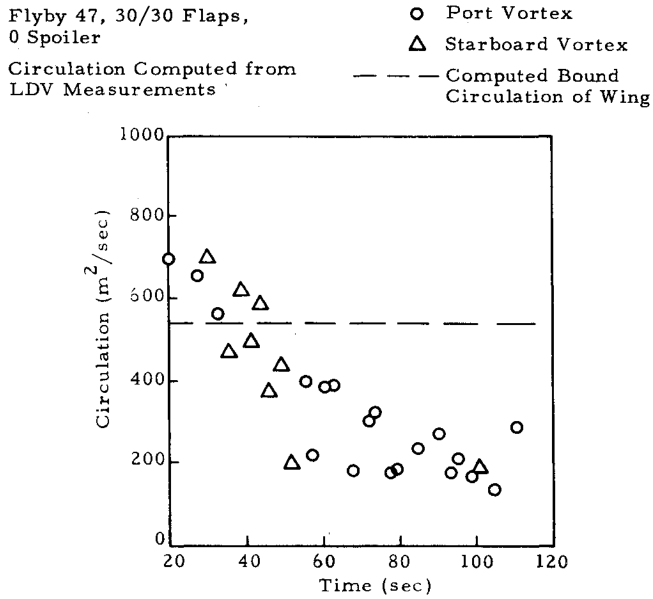


Fig. 9 Wake vortex circulation as a function of time.

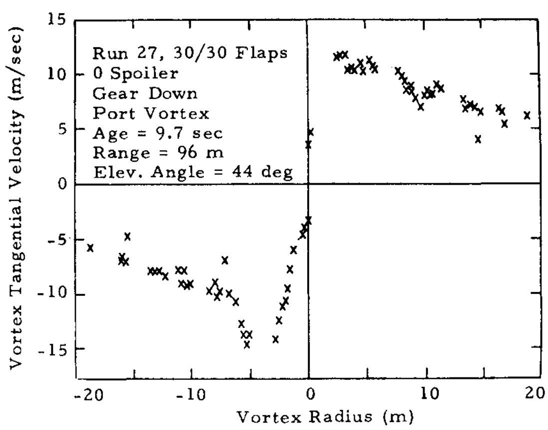


Fig. 8 Wake vortex tangential velocity as a function of radius from LDV finger scan of B-747 wake.

$C_L = 1.41$, airspeed $U_\infty = 69.5$ m/s, wing chord $\bar{c} = 8.3$m, and spanwise loading coefficient $K = 0.762$, $\Gamma = \frac{1}{2} U_\infty \ \bar{c}(C_L/K) = 534 \ \text{m}^2/\text{s}$, is also shown.

While the finger scan technique is useful for establishing the vortex trajectory, the arc scan technique is useful for measuring the details of the vortex flowfield. Both of these scan techniques demonstrate specific advantages and limitations. In the finger scan technique the backscatter intensity or the one-dimensional velocity information is utilized to identify the centroid of the two vortices and to discriminate between the port and starboard vortex. The processing algorithm functions best when both vortices are located within the scan limits and are equidistant from the LDV. If one vortex is significantly closer to the LDV than the other, the vortex tracking algorithm may neglect the weaker amplitude signal of the farther vortex. This is illustrated by the predominance of the port over the starboard data points occurring in the LDV measurements shown in Figs. 6 and 7. Thus, the finger scan technique is particularly useful for obtaining a coarse definition of the vortex trajectory over large scan limits.

In contrast to the finger scan technique, the arc scan technique provides a detailed definition of the vortex flowfield over small scan limits. Since the vortex pair rapidly descends through a given arc scan at predetermined ranges, a so-called stepped arc scan, could be used to track the vortex pair.

The LDV measurements obtained at Rosamond illustrate the ability of the ground-based remote sensor to charactrize aircraft wakes. Based on experience obtained at Rosamond, the wake measurement capability of the LDV system was extended through 1) the addition of real-time velocity processing and display capability, 2) the addition of automated stepped arc scan capability, and 3) the development of improved algorithms for determining vortex location and circulation strength. To refine further the measurement capability of the system, new concepts are currently being investigated including the coordination of the scans from two LDV vans, the processing of the LDV signature to obtain both the line-of-sight and transverse velocity component and the development of algorithms to extract the wake vortex signature from the ambient wind field and noise using statistical techniques.

Ship Wake Measurements

The influence of large naval vessels upon the atmosphere around them has been recognized for years. These localized atmospheric distrubances have been especially troublesome in connection with the operation of aircraft from the decks of ships. Considerable effort has been expended in modeling these atmospheric phenomena using both water and wind tunnels. However, until the development of remote atmospheric sensing (specifically laser Doppler sensing), validation of these mathematical models with full-scale testing has been extremely difficult.

In May 1975, the Lockheed LDV was deployed aboard the nuclear carrier U.S.S. Nimitz (Fig. 10) during Automated Carrier Landing System certifications[10] for a feasibility test demonstration. The test program was designed to determine the feasibility of remotely monitoring atmospheric flowfields in regions both fore and aft of the ship. The data aft of the ship (in the region of the ship's burble) would be used in conjunction with aircraft landings (traps), and the bow measurements would likewise be used with aircraft launches. This paper will present some of the remote measurement data taken aft of the ship.

During testing, the LDV van was located just forward of the aircraft touchdown zone and over the angled deck centerline (Fig. 11). The system was configured to range scan at a 1-Hz rate and manually step from an elevation angle of 1.5 to 5.5 in 0.5-deg increments.

The testing was designed to coincide with the Naval Air Test Center's calibration of the Nimitz's anemometer system. A temporary 30-ft tall anemometer calibration boom was

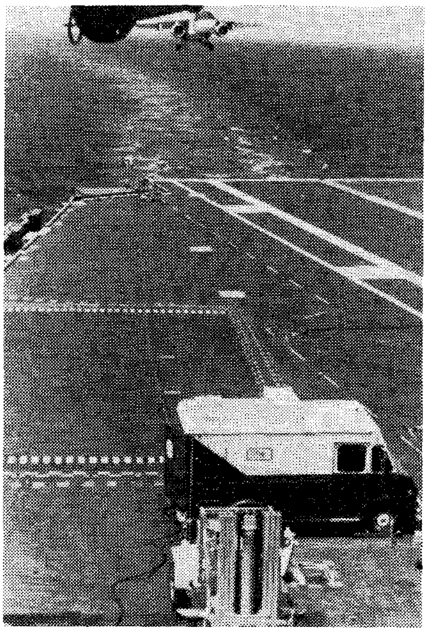


Fig. 10 Mobile laser Doppler system mapping burble during S-3 approach.

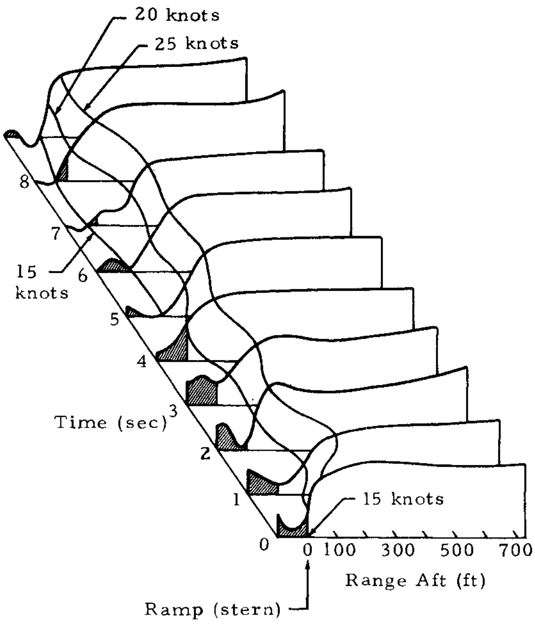


Fig. 12 Consecutive LDV range scans taken at 1-s intervals along the 3.5-deg glide slope.

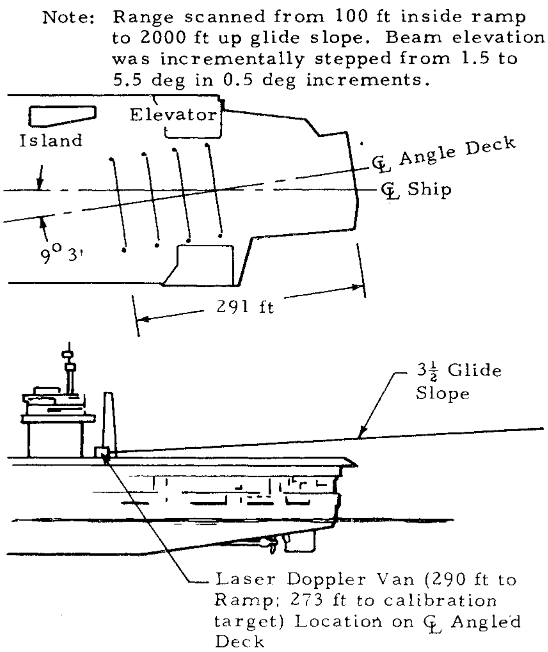


Fig. 11 Van location and aft scan pattern.

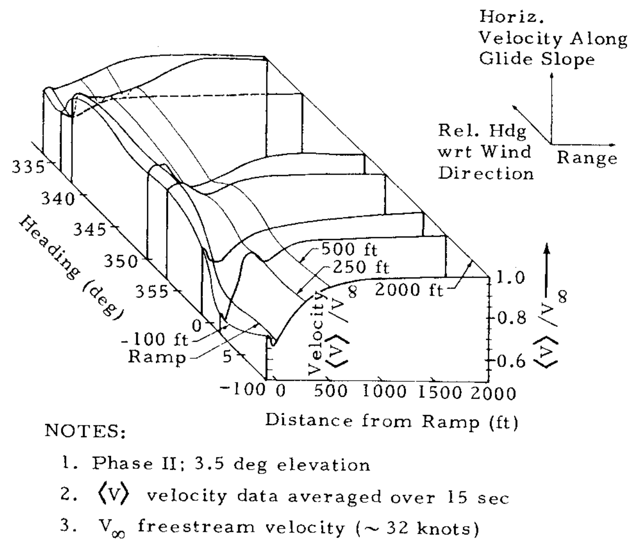


Fig. 13 Normalized line-of-sight velocity in burble as a function of relative wind-over-deck heading (30- to 35-knot case recorded May 6, 1975).

erected on the flight deck near the bow of the ship. The ship was scheduled to maintain a number of specified relative wind-over-deck (WOD) headings and speeds during the calibration period. Each calibration period segment was designed to allow several readings from each anemometer system during a single specified relative WOD condition. This would allow roughly nine 15-s recordings of 0.5-Hz range scanning data for a specified WOD heading. Each 15-s recording would be at a different elevation angle beginning at 1.5 deg and stepping through to 5.5 deg in 0.5-deg increments.

Figure 12 depicts the wind velocity along the aircraft glide slope for a sample period of approximately 10 s while the ship was sailing a constant WOD heading and speed of 002 deg and 30 knots, respectively. The 10 curves of the figure represent 10 consecutive range scans 1-s apart. The line-of-sight wind velocity is plotted vs range. The range is measured aft from the ramp (ship's stern). The vertical scale line-of-sight velocity magnitude ranges from 15 to 30 knots. The temporal variations in the wake are considerable between the −100- and +300-ft points (aircraft touchdown at approximately the −100-ft point) indicative of a substantial turbulent velocity deficit.

Figure 13 depicts averaged ship's wake characteristics as a function of the ship's relative heading with respect to the ambient wind (as measured by the ship anemometer system). Data for a number of plots such as those of Fig. 4 were averaged to derive the plot for each heading of this figure. The van was placed in the same position and again scanned aft along the glide slope. While Fig. 12 depicts velocities out to a range of 700 ft, the velocities of Fig. 13 extend out to 2000-ft range. The velocity measurements were normalized by dividing by the velocity measured at a range of approximately 2000 ft aft the ramp.

Ideally, a 350-deg WOD heading is chosen for landing aircraft. This positions the ship such that the wind is directly down the flight deck. As indicated in Fig. 13, burble con-

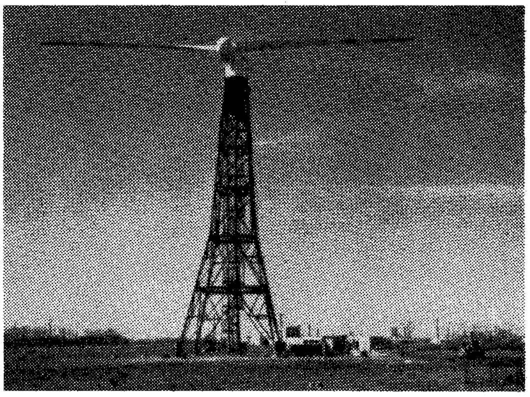


Fig. 14 NASA wind turbine at Plum Brook Station, Ohio.

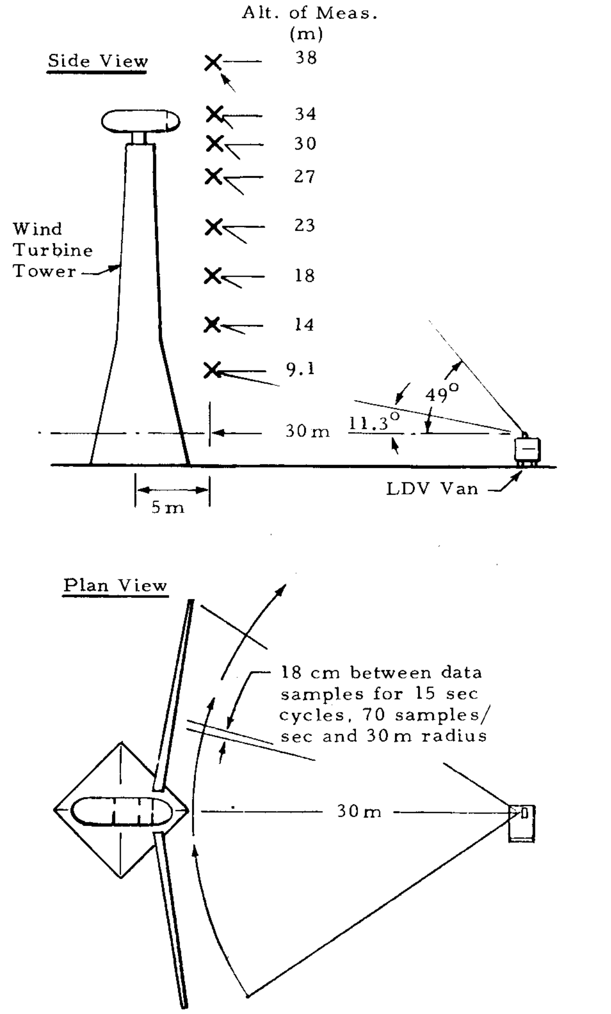
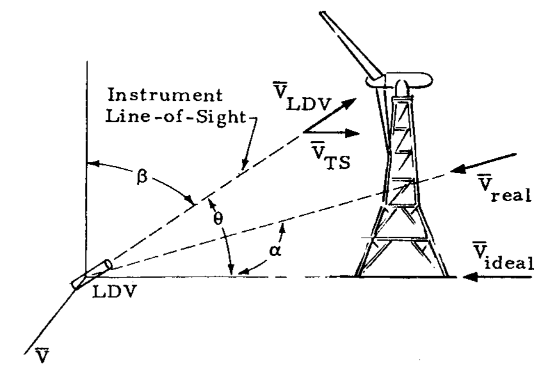


Fig. 15 Schematic of test configuration for wind turbine tower wake surveys.

ditions are also much less severe than for headings of 0 to 10 deg or 330 to 335 deg. However, if under combat conditions aircraft are landed at some of the nonideal WOD headings, the pilot not only has to compensate for the crosswind, he must also penetrate the unseen severe burble condition.

Other LDV measurements from the Nimitz tests depicted flow variability, both forward and aft, as a function of scan elevation angle and range, and wind shear above the ship as a function of altitude. These remote measurements indicated that a compacted, automated LDV would offer considerable potential for supporting the ship's Automatic Carrier Landing System and Catapult Launch System.



$\bar{V}_{LDV}$ = line-of-sight velocity measured by laser Doppler velocimeter

$\bar{V}_{ideal}$ = preferred wind direction (i.e., blowing from tower toward van)

$\bar{V}_{real}$ = actual average wind direction during 15 sec conical scan (displaced from ideal by azimuth angle, α)

θ = elevation angle between horizontal and instrument line of sight $= (90^o - \beta)$

$|\bar{V}_{TS}|$ = horizontal velocity within tower shadow $= |\bar{V}_{LDV}| \div \cos\theta \div \cos\alpha$ where combined corrections were typically < 10% (i.e., $\cos\theta \div \cos\alpha \sim .90$ or larger)

Fig. 16 Graphical description of cosine corrections.

Wind Turbine Tower Wake Measurements

NASA/DOE studies have indicated large wind turbines, 500 to 1500 kW and above, appear to offer the potential for delivering electrical energy at costs that are competitive with several conventional power generating systems. The resulting sizes of these turbines for nominal wind speeds of 12 to 20 mph are large (Fig. 14) with supporting structures typically 30 m or more in height and rotor diameters of 30 to 60 m. The large sizes of these structures, the relatively low air speeds involved, and the variability of winds have rendered impractical most conventional techniques for full-scale monitoring of flowfields about the structures. The desirability of a remote sensor for full-scale flowfield testing is obvious.

The LDV van was deployed at the NASA test facility at Plum Brook Station, Ohio, to measure the deficit in the wind flowfield in the wake of the support structure.[11] The wind defect, known as the tower shadow effect was believed to be the source of larger than expected wind loading upon the turbine rotor structure. A byproduct of these LDV surveys was information on the unsteady flowfield perturbations monitored approximately 65-m downwind of the turbine tower. All tests were conducted with the turbine blades feathered horizontally.

To measure wind speed in the tower wake, the LDV van was located approximately 35-m downwind of the tower (Fig. 15). The system was scanned in a cylindrical fashion to provide the line-of-sight velocity component between the van and tower at eight altitudes along and above the tower profile. The system was focused at a range of approximately 5-m downwind of the tower centerline and was horizontally scanned to provide the velocity distribution at each altitude.

Since the LDV measures the line-of-sight velocity component of the wind, the ideal tower wake survey would be to translate the LDV van downwind along the centerline of the tower wake. However, the winds were variable during the tests. A more practical approach was taken to fix the van in one downwind location and to compensate for wind direction shifts with cosine corrections. The cosine corrections are depicted in Fig. 16. The typical cosine corrections were relatively small in magnitude at lower levels and higher near

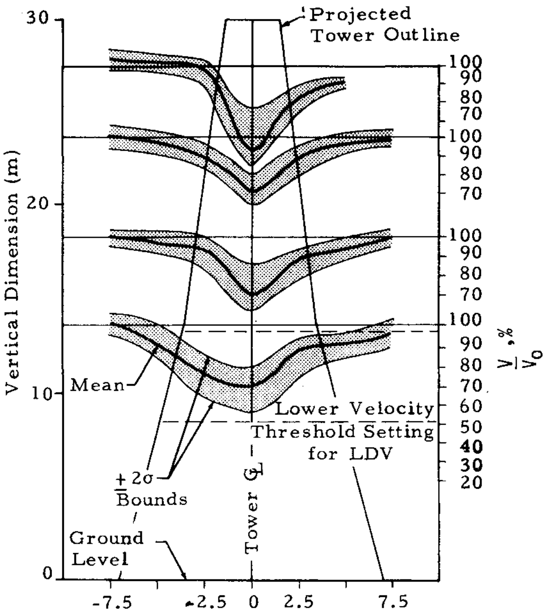


Fig. 17 Ratio of measured velocity to freestream velocity for seven scans through the tower shadow at each of four altitudes.

the hub. For example, the elevation angle corrections varied from 2% at the 9.1-m level to 26% at the wind turbine hub level (30 m).

The normalized velocity profile measurement, for a number of scans across the tower wake is depicted in Fig. 17. Cosine corrections (Fig. 16) have been applied to the data. The tower outline is sketched in the background. The left-hand vertical scale represents tower height dimensions. The measurements are shown at four altitudes. The right-hand vertical scale represents velocity (V) normalized by the freestream velocity (V_0). The horizontal scale is distance along the scan measured relative to the tower centerline.

The mean velocity deficit plus an envelope which shows the ± 2-sigma variation of the data points are shown in Fig. 17. These temporally averaged velocity deficits appear considerably broader than the tower structure itself. Some broadening is due to the averaging of seven scans at each level with 90 s elapsing during the total recording period at each level. Since the freestream wind at hub height was only 16 knots, the wind direction shifted considerably during the test period. This wind shifting tended to smear the data horizontally causing the deficit plots to be broader and less depressed than measurements made over a short period of time.

A more severe deficit is noted at the 23.7-m level than at the lower levels. Upper-level portions of the tower were enclosed with canvas during the testing which attributed to increased blockage and thus increased deficit over the more open lower levels.

Wind-tunnel testing was conducted by NASA[12] on a 1/25-scale model of the tower at a slightly different viewing angle (somewhat more blockage). The scaled testing indicated a greater velocity deficit than did the full-scale tests. It is conjectured that the tower wake deficit exceeded the low velocity threshold chosen for the LDV which would explain this measurement discrepancy.

The tower wake survey tests indicate considerable potential for the LDV in measuring full-scale building wakes and for monitoring other large structural wakes. Moreover, for the wind energy program the LDV should prove very useful for monitoring the extent of wakes from full-scale operational wind turbines.

Conclusions

Capabilities of laser Doppler instrumentation for remote sensing of multidimensional atmospheric flowfields have been clearly demonstrated. The Laser Doppler Velocimeter is capable of accurately monitoring full-scale flowfields associated with large aircraft wakes, the atmospheric environment of ships at sea, and wind deficits in the wakes of large wind turbine structures. Instrumentation and technology are available for performing these types of remote sensing tasks. Valuable aerodynamic and flowfield data can be gleaned by extending the testing methodology described herein.

Acknowledgment

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