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Abstract

The Langley Research Center of the National Aeronautics and Space Administration is currently engaged in basic research to improve aerial appli ations technology. As part of this program, Langl y's Vortex Research Facility and Full-Scale Wind Tunne play lead roles in aircraft systems research to improve aircraft aerodynamics and dis ersal systems efficiency, and in studies of aircraft wake-dispersal interactions to improve drift control and dispersal transport.

In the Vortex Research Fa ility, small-scale models of agricultural airplanes are tested and numerical methods are utilized to study interactions between the airplane wake and the dispersed spray and granular materials. Methods are being developed to measure and predict dispersal transport and ground deposition with the objective of modifying wake characteristics and dispersal techniques to obtain interactions more favorable to wide, uniform deposition patterns and reduced drift. In the Full-Scale Wind Tunnel, full-scale agricultural airplanes and dispersal systems for both liquid and solid applications are evaluated to improve aircraft aerodynamics and dispersal systems efficiency. This paper presents the program status in these two facilities with emphasis on wake interactions and dispersal systems research.

Introduction

The use of aircraft in agriculture began more than fifty years ago (ref. 1). Since that time aircraft have continually expanded their usefulness in many phases of agricultural production, with the advantage of their use being speed of operation and ability to apply material when and where ground application is either impossible or impractical. Today the agricultural aircraft industry is an important component of the modern, mechanized agricultural society. The current world fleet consists of over 24,000 aircraft with about 8,600 fixed and rotary winged aircraft used primarily for agricultural purposes in the United States alone. In 1976 the U.S. fleet flew about 2.5 million hours treating some 180 million acres. Revenues in excess of a billion dollars were realized from these operations. The industry has experienced an annual growth rate of about 12 percent over the past several years (ref. 2).

Until about 1950 aircraft used in agriculture in this country were designed originally for other purposes. Military trainers were the most widely used, because they were available at extremely low cost as surplus after World War II. Dry materials spreaders and spraying equipment were designed, fabricated, and installed in the field by operators themselves.

Today's agricultural airplanes have improved, but for the most part they are still typical of the design technology of the 1930's. A modern-day Thrush Commander agricultural airplane, for example (Figure 1), employs an uncowled radial engine and lacks filleting in wing-root-fuselage juncture areas-as was representative of airplanes flown in the 1930's

Design technology for dry material spreaders and spraying systems is also primitive in many respects. Equipment is externally attached under the aircraft fuselage or wings, and no systematic approach has been applied to integrating the system with the aircraft for maximum dispersal efficiency and aircraft performance.

Two serious problems facing the industry are drift of toxic chemicals from treated areas and nonuniformity of coverage on crops, which result in large loss in productivity in terms of chemical waste and environmental or health hazard. In fact, a recent poll of agricultural aviation users listed chemical drift as the single most serious problem facing the agricultural aviation community (ref. 3). A major cause of drift and nonuniform coverage is the interaction of the aircraft wake with the dispersed material. An example of wake-spray interaction is shown in the photograph in Figure 2.* Principal regions where strong interactions occur are in the wing-tip vortex flow, where small particles are entrained and remain airborne, becoming more susceptible to drift; and in the propeller slipstream, where material is given a lateral bias. Typical effects of these interactions on the deposition pattern (single-swath concentration of material on the ground) are illustrated in Figure 3, which shows a comparison between ideal and actual patterns. The trapezoidal pattern (dotted line) is desirable because the sloping sides of the pattern overlap on adajacent swaths, permitting some variation in lateral swath accuracy (spacing) without overly degrading uniformity of coverage. Large differences are apparent between ideal and actual patterns illustrated in Figure 3, in terms of both total deposit and pattern shape. The amount of chemical deposit in the swath is often considerably less than the amount applied, and the pattern shape is not uniform but contains regions of both over and under chemical concentration. With medium sprays (300- 00 microns Volume Median Diameter), for instance, only 70 of applied chemical may be recovered within 305 meters (1000 ft.) downwind of

*Photograph courtesy of World of Agricultural Aviation Magazine the flight path even with relatively low altitude application (material released under 3.05 meters height) under low wind conditions (5-8 Km/hr) (ref. 1). Interaction of the aircraft wake with the dispersed material, therefore, seriously degrades overall application system performance by increasing the potential for drift and decreasing the quality of coverage.

The purpose of the present paper is to summarize the current status of research on aerial applications in the Vortex Research Facility and Full-Scale Wind Tunnel with emphasis on wake-dispersal interactions research.

Nomenclature

- b wing span
- C_D drag coefficient
- c wing chord
- d propeller diameter
- g acceleration due to gravity
- h height above ground plane
- n propeller rotational speed
- R Reynolds number
- t time
- U flow velocity
- U_∞ Airplane or free stream velocity
- Γ total circulation of wing
- Γ_p total circulation of propeller
- δ particle diameter
- Θ_p angular propeller position
- μ absolute air viscosity
- $\bar{r}$ particle position vector
- ρ air density
- σ particle density

Research in Vortex Facility

Objectives and Approach

Wake-dispersal interactions are studied in the Vortex Research Facility by means of tests with small-scale models and by use of numerical methods. The broad objective of this research is to determine how to integrate airplane wake characteristics with dispersal techniques in such a manner as to improve overall application system performance.

Aerodynamic wake modification is believed to be a means by which wake-dispersal interactions may be improved. The objective of wake modification is to minimize undesirable effects of wake flow such as the entrainment of fine spray droplets in the wing tip vortex, while maximizing desirable effects, such as lateral transport of relatively large particles, liquid or granular (seed and fertilizer), which increases deposition pattern width. Technology developed through NASA's wake vortex minimization program is drawn upon to guide studies to identify candidate concepts for wake modification. Concepts found to be promising from scale model tests in the Vortex Facility, and numerical simulations, are validated by correlation with full scale tests, both in wind tunnels and in flight. Throughout this development, candidate concepts are evaluated to determine their effects on airplane performance, stability, and control, in order to determine flightworthiness and practicality. Concepts include both practical devices for retrofit to existing aircraft and new design considerations for future aircraft.

During the past year, efforts have been underway at the Vortex Facility to develop and validate the experimental and theoretical research tools required to conduct research on wake-dispersal interactions. The principal objectives of this early activity are: first, to develop methods to simulate aerial dispersal; second, to develop a data base to quantify wake and dispersal characteristics; and finally, to examine wake modification as a method of producing favorable changes in deposition characteristics. Wakes generated by scale models of agricultural monoplanes and biplanes were examined with flow visualization and laser velocimeter flow measurements; and wake properties were computed with numerical techniques. Scaling laws were derived for trajectories of particles released in the wakes of agricultural airplanes to establish test similitude for dispersal of dynamically-scaled particles from model airplanes. Concurrent with this scaling development, experimental techniques were developed to release scaled test particles in the model wakes and measure trajectories and deposition patterns. Finally, exploratory tests were conducted on a number of candidate concepts for wake modification to evaluate their effect on wake vortex flow, and the effects of one concept, wing tip winglets, on deposition were measured using the newly developed dispersal test methods.

Description of Facility

The Vortex Facility, shown in the sketch in Figure 4, was used during the 1940's and 50's as a towing tank and an impact basin to study stability, control, and performance of seaplanes and ditching characteristics of landplanes. During the past decade, the facility was converted to study the upset hazard associated with the strong wake vortices generated by large jet transport aircraft. In October 1976, the facility was further modified to permit testing of models of agricultural aircraft in ground effect.

The particular feature of this facility is that the test airplane model is moved through a stationary medium (air) rather than being held stationary while the test medium is forced by it as in conventional wind tunnels. This test mode permits observation of the model-generated wake for large distances behind the model aircraft from a ground based station at rest with respect to the air.

The facility is 550 meters long and has an enclosed overhead track extending the length of the building. The wake generating airplane model is blade mounted on a strain-gage balance beneath a streamlined powered carriage, which travels along the overhead track. The support blade is adjustable to permit variation in model altitude and pitch. The model aircraft is towed at constant velicity through a test section enclosure which serves to isolate the carriage wake from the model. Test measurements are taken as the model passes over a ground plane installed in the test section. The test section is 91 meters long, 5.5 meters wide, and 5.2 meters high with a 5-cm wide opening in the ceiling to allow the model support blade to pass. The overhead track extends 305 meters ahead of the entrance to the covered area to permit the carriage to accelerate to test velocities up to 30 meters/sec.

Wake Studies

Wake vortex systems generated by the model airplanes are studied with flow visualization and laser doppler velocimetry. The flow visualization technique, which was developed at the facility, has proven quite suitable for obtaining time histories of wake development and decay. A screen of kerosene smoke, generally confined to a plane perpendicular to the model flight path, is injected into the facility test section and allowed to become stationary. The model is then propelled through the smoke and the wake action, made visible by the smoke induced along the flow streamlines, is recorded photographically with high-speed cameras. A detailed description of this flow visualization technique can be found in reference 4. A recent refinement of the technique improves the visual data by utilizing a thin "sheet" of light projected by a high intensity mercury-arc lamp to illuminate the smoke only in the plane.

Use of this technique for qualitative studies is demonstrated in Figure 5 which shows a comparison of monoplane (upper photo) and biplane (lower photo) wake development about three and one-half wing semispans downstream of the airplane. In these photographs, the models are shown in three-quarter front perspective passing from right to left across the visual field. Models are at attitude corresponding to typical lift conditions during a swath flight pass, out of ground effect, with flaps retracted.

Differences between monoplane and biplane wake development can be clearly seen in the photographs. The monoplane wake quickly rolls up into a single vortex from each wing, left and right, whereas the biplane wake develops into two vortices on each side, one from each wing panel, upper and lower (the biplane wing panels were operating at similar lift coefficients). The two vortices on each side of the biplane wake rotate about each other (in direction indicated by arrow), orbiting about the centroid of vorticity associated with that side of the wake. Both vortex systems, monoplane and biplane, are characterized by highly swirling flows, particularly near the vortex cores. It is this phenomenon which causes the entrainment and subsequent drift of spray droplets.

The flow-visualization technique is also used for quantitative wake studies. An example of this use is presented in Figure 6, which shows a comparison of monoplane and biplane vortex trajectories in ground effect. Time variation of vortex core position is determined from photographs similar to those in Figure . and is plotted as a function of distance behind the aircraft, in wing semispans (indicated by the numbered ticks on the data curves). Scaled front-view drawings of the model airplanes at test altitude are included on this and subsequent figures as a graphic aid. Vertical and horizontal scales are height above the ground plane and lateral distance from the flight path, respectively, in wing semispans. Lower flight paths (monoplane wing tip and biplane lower wing tip at height of 0.34 semispans) are typical of low altitude, "on-the-deck", applications. Data are also presented for the monoplane at higher altitude (wing tip at height of 0.78 semispans) for comparison. Models are at attitude corresponding to typical lift conditions during a swath flight pass.

The main effect of ground proximity is to restrict the normal vertical descent of the vortex below the wing tip and to cause a rapid outboard movement of the system laterally over the ground. As airplane height above the ground is increased, the vortex drops below the wing tip and moves outboard more slowly. This decrease in vortex lateral transport velocity with increase in airplane altitude is seen by comparing vortex lateral position at equal distances behind the airplane for the two altitude cases presented for the monoplane.

Again, differences between monoplanes and biplane wake characteristics are apparent. The two vortices on each side of the biplane wake rotate about each other, the trajectory of each strongly affected by the presence of the other vortex. Eventually, forty-to-fifty semispans behind the airplane, they merge into one vortex. The path which this vortex system takes as a whole, however, is similar to that of the single vortex from one wing of the monoplane.

An interesting phenomenon observed in these data is the upward migration or rebound of the vortex system away from the ground as it moves laterally outboard (note vortex upward movement for monoplane low-altitude case beginning about 15 semispans behind the airplane, for instance). Vortex rebound has been observed numerous times by researchers measuring vortex trajectories, both behind agricultural airplanes (ref. 5 for example) and more recently behind transport airplanes at airports (ref. 6). The phenomena has been explained as resulting from the viscous "scrubbing" action of the vortex on the ground (ref. 7). Vortex lateral motion close to the ground causes the boundary layer at the ground to grow and separate, resulting in a secondary vortex which induces an upward velocity to the primary vortex system. Another factor possibly contributing to the amount of rebound seen in Figure 6 at relatively large distances behind the airplane, say forty or fifty semispans, may be interference resulting from proximity of the test section side walls. With the one-sixth scale model used to generate this trajectory data, the walls are 2.77 semispans from the model flight path. Calculations suggest some wall effects on trajectory data for this size model but indicate they are small for at least thirty semispans behind the model.

Large differences between wakes generated by monoplanes and biplanes are apparent in Figure 5 and 6. The significance of these differences in terms of their effect on ground deposition patterns is largely unknown; however, one can appreciate that such differences may well be significant, and that knowledge of them is likely to be important for understanding the interactions which occur.

Wake characteristics are also studied quantitatively with a recently developed rapid-scan two-dimensional laser doppler velocimeter (LDV). The LDV capability, developed at the facility for the Wake Vortex Minimization Program, is capable of simultaneously measuring both vertical and axial (along flight path) velocity components in a near or far-field wake vortex system. Its applicability to wake studies for agricultural airplanes, where vortex systems are often rapidly transporting in ground effect, has recently been demonstrated (ref. 8).

The LDV system is operated in backscatter mode. The technique utilizes an unique optical scanning system (ref. 9) which permits rapid incremental scanning of the laser focus point over the measurement region up to 30 times a second. As the vortex moves down and across the ground plane, it crosses the laser optical axis in the measurement region. Vertical velocity measurements through the vortex core (which measure the maximum tangential or swirl velocities in the vortex) are obtained as the vortex crosses the optical axis. The sketch in Figure 7 illustrates the relation of the laser beams to the vortex and presents a representative vertical velocity profile through the vortex core. The laser is beamed horizontally across the test section perpendicular to the model flight path. In the velocity profile presented, vertical velocity, U , normalized with respect to the airplane test flight speed U_∞, is given as a function of spanwise distance, y , from the wing tip in semispans. As seen in Figure 7, maximum flow velocities near the vortex core are about thirty percent of flight speed. Such velocities are large compared to settling (terminal) velocities of small droplets in air. For instance, the settling velocity of 250 micron size water droplets is only about 1 m/sec in still air compared to maximum vortex swirl velocities of about 13 m/sec for a typical flight speed of 45 m/sec (100 miles/hr.). It is understandable how behavior of even large droplets sprayed from nozzles near the wing tip can be dominated by vortex flow dynamics and how vortex entrainment can be the inevitable fate of smaller droplets.

In addition to wake flow measurement, analytical prediction methods are also used to study wake properties. A powerful tool recently developed for the NASA Wake Minimization Program is a computer program with the capability of calculating the fully turbulent flowfield behind an aircraft, including its viscous interaction with the ground (ref.10). An analytical method which utilizes this computer program has been developed to predict properties of wakes in ground effect for agricultural airplanes (ref. 11). The method combines three separate computer programs. The first is a finite element scheme to solve the lifting surface potential flow problem. This computer program has the capability of handling nonplanar auxiliary lifting surfaces, such as winglets. Wing geometry is input to the program, and output defines the loading of the wing. This loading is then input into the second computer program which uses an inviscid Betz vortex roll-up procedure, modified to allow multiple vortices in the wake, to compute spanwise location and strength of rolled-up wake vortices. Initial rolled-up vortex strength and location are then input to the viscous wake computer program, which solves a reduced system of the Navier-Stokes equations using a finite difference scheme, to compute wake vortex properties at distances behind the airplane. Properties such as vortex strength and location, as well as induced velocity field, may be predicted in the aircraft wake.

A comparison between a vortex trajectory measured in the facility (previously presented as the low-altitude monoplane case in Figure 6) and a numerical prediction of the trajectory using the analytical method described herein is presented in Figure 8. Simulation of test section side walls is included in the numerical model to permit direct comparison with facility data to fifty semispans behind the airplane. This comparison shows very good agreement between computed and measured vortex trajectories. Future plans are to interface this computer program with a particle dynamics numerical model to permit studies of interactions between dispersed particles and the airplane wake.

It is anticipated that these experimental and analytical capabilities will be valuable research tools for gaining a better understanding of wake dynamics and for evaluating the effectiveness of candidate concepts for aerodynamic wake modification for more efficient aerial applications.

Wake-Particle Interactions

During the past year, a large effort has been underway in the Vortex Facility to develop analytical and experimental methods to simulate wake-particle interactions. Scaling laws have been derived for test similitude with dynamically scaled particles. This analysis permits results of scale model tests in the facility to be extrapolated to full-scale conditions. Initially, scale parameters were derived for liquid droplets (ref. 12); the analysis was then extended to include the case of dry granular materials, such as fertilizers and seeds (ref. 13).

The scaling analysis for liquid particles is for the trajectories of droplets from 100 to 500 microns in size injected into the wake of an airplane. Such droplets are nearly spherical in shape, permitting the classical drag variations for spheres to be used. The wake velocity vield is modelled using potential flow theory. After reducing the equation of motion for the particle to inertial, drag, and gravity terms, the scaling derives the following parameters upon which the particle position vector, $\bar{\eta}$, is functionally dependent.

$$\bar{\eta} = G\left(\frac{U_\infty^2}{bg}, \frac{\Gamma}{U_\infty b}, \frac{U_\infty t}{b}, \frac{h}{b}, \frac{\Gamma}{\Gamma p}, \frac{U_\infty}{nd}, \frac{d}{b}, \sigma p, \frac{\rho\delta U_\infty}{\mu}, \frac{\rho^2 U_\infty^3}{\sigma g \mu}\right)$$

(eq. 12, ref. 12).

This scaling gives a one-to-one correspondence between scaled test particle and full-scale prototype droplet, for a given scale. That is, once size and density of full-scale droplet is specified, the scaling procedure uniquely fixes the size and density of the test particle. As seen above, the parameter which establishes particle density requires the scaled particle to be less dense than its full-scale prototype. A difficulty arises in that typical test scales require very light particles, which may be difficult for the experimenter to obtain or work with. Also, an assumption made in the analysis is that the ratio of the particle density to air density is large, and this assumption may be violated at test scale.

These problems have been circumvented by a modification to the scaling analysis in which the particle drag curve is approximated by $C_D = BR^{\gamma}$, (eq. 14, ref. 12) where B and γ are constants to be determined for the range of particle Reynolds numbers of interest. This approximation allows the last two terms in the scaling equation to be replaced by $\frac{\mu^{1+\gamma}\delta^{\gamma-1}U^{2+\gamma}}{\sigma g u^{\gamma}}$ (ref. 12). With this approximation, the constraint for unique size and density correspondence of scaled particle to prototype is relaxed and test particles with a broad combination of size and density are allowable for a given test scale.

Concurrent with the scaling development, a test method was developed to disperse scaled particles from the model airplanes and measure their trajectories and ground deposition patterns. Some aspects of the method are illustrated in Figure 9. Currently, several types of spherical test particles such as expanded polystyrene (figure upper left), glass, and fillite are being used in tests. Particle size, density, and shape are held to close tolerances. Hoppers (cylindrical containers) to contain the particles are molded into the model wings (figure upper right) or mounted separately in spanwise troughs inside the wings. Particles are gravity-fed to nozzles (figure lower left) located in the wing lower surface. Nozzle shapes are designed to confine particle ejection to "single-point" as closely as possible. Particles can be ejected from a wide range of dispersal points, including spanwise, chordwise, and vertical positions. A pulsed "light curtain" perpendicular to the model flight path illuminates particles in the model wake, and trajectories are recorded by streak photography as dashed lines across the visual field (figure lower right). Pulsing the light source allows particle velocities to be measured. In Figure 9 the model wing is shown in three-quarter front view crossing the visual field from right to left, about one third semispan above the ground plane. Dispersal is from a single nozzle located near the wing tip. Particle trajectories can be clearly seen, in most cases, from ejection to the ground.

Deposition patterns are measured by collecting particles in spanwise sample regions at stations along the model flight path and then expressing particle concentration as a function of lateral distance. Figure 10 shows the effect of airplane lift on lateral displacement of single-nozzle deposition. The range of lift is typical of the change in airplane gross weight during operations. In these tests glass spheres of density 2.42 g/cm3 were scaled to a diameter of 105 microns to represent 371 micron diameter full-scale water droplets. Particle concentration is expressed as percent of total deposit and plotted as a function of lateral distance from flight path. The data illustrate that lateral displacement of deposition is quite sensitive to relatively small changes in lift, with an increase in lateral transport of the particles associated with increased lift. In addition, an increase in lateral spread and reduction in peak values with increased lift can be noted. This occurs because particle trajectories become more nearly parallel to the ground and disperse more before impact for the higher lift cases. Because of the substantial dependence of deposition on lift (or alternately vortex strength), such measurements may be sensitive indicators for evaluating concepts for wake and dispersal modification.

Using these test methods, a preliminary validation of the particle scaling has been conducted (ref. 12). Two types of test particles, expanded polystyrene and glass, which differ greatly in density (density of polystyrene is .065 g/cm^3 or less than three percent of glass, 2.42 g/cm^3) were sized by the scaling laws to represent approximately the same size water droplet (371 microns for glass compared to 396 microns for polystyrene). The resulting particle sizes required by scaling also differed greatly (diameter of polystyrene sphere was 1000 microns, or nearly ten times that of glass, 105 microns). The two types of particles were released into the model wake from single nozzles in separate test runs over a range of lift coefficients (vortex strength), and depositions were compared in terms of lateral position of median. The comparison presented in Figure 11, shows good agreement between the two types of particles, validating the scaling. Since the validation did not include comparisons between airplane models of different scales, and since full-scale depositions are not available for comparison, only the particle dynamics scaling is validated in these tests. A more complete validation which includes a verification of aircraft wake scaling, is currently underway at the facility. These tests, in which results are being compared between models of different scale, are expected to establish a test envelope for the Vortex Facility.

In addition to this experimental method for measuring wake-particle interactions a numerical code has been developed to calculate such interactions (ref. 14). In this computer program airplane and propeller wakes are modeled by potential flow theory. Simulation of ground, facility test-section walls, cross-wind component and particle evaporation is included. A step integration technique is used to solve the equations of motion for the particle, which is assumed spherical. To demonstrate use of the program typical calculations of water droplet trajectories and depositions are presented in Figure 12. (Calculated depositions assumed droplet size distribution for the nozzle to be normal with a mean of 200 microns and a standard deviation of 50 microns). This figure clearly shows both the beneficial and harmful effects of vortex flow on particle transport. The larger, heavier droplets, particularly those ejected from nozzles located more outboard, receive a large spanwise velocity component from vortex circulation. As mentioned earlier this lateral transport is largely responsible for the wide swath widths that are obtainable. The smaller, lighter droplets, on the other hand, may be entrained in the vortex if ejected too close to the wing tip, and may aggravate the drift problem. Trajectories in the upper half of Figure 12 show vortex entrainment of the 100 micron droplet ejected from the most outboard nozzle. Depositions, presented in the lower half of Figure 12, show reduction in peak concentration and increased lateral spreading associated with more outboard nozzle locations. The computer program also calculates percent of driftable material by subtracting the amount of material deposited from the input nozzle flow rate. Future plans are to interface the particle dynamics model in this computer program with the more sophisticated viscous wake vortex model previously described in this paper under "Wake Studies."

Wake Modification

A number of methods of aerodynamic wake modification have evolved through efforts of researchers to minimize the vortex wake hazard. These methods alter wake properties through use of aerodynamic flow mechanisms (tailoring spanwise circulation, or injecting turbulence for example). Several candidate concepts for modifying wakes of agricultural airplanes are shown in Figure 13. Use of some of these concepts may improve drift control because they are known to attenuate vortex flow at the wing tip (splines (ref. 15) or winglets (ref. 16), for example), while use of some may increase effective swath width because they enhance spanwise flow under the wing (span loading alteration, for example).

Exploratory tests have been conducted with several of the illustrated concepts. Recently, effects of both splines and winglets on the wing tip vortex were measured, and using the recently developed test techniques for particle dispersal, effects of winglets on deposition were measured. Effectiveness of a relatively small spline (spline diameter = 0.26c) as a vortex attenuator is demonstrated in Figure 14. Results indicate substantial reduction in large swirl velocities near the vortex core. With splines installed, flow in the core region is relatively disorganized and peak vertical velocities are reduced about fifty percent. Although it is not yet known if such reduction is sufficient to significantly reduce droplet entrainment, these results nevertheless demonstrate that substantial vortex attenuation can be achieved.

Winglets have been identified as a concept meriting evaluation for use on agricultural airplanes because they are known to cause a vertical diffusion of the tip vortex flow just downstream of the wing tip (ref. 16). Effects of winglets on the vortex in ground effect, presented in Figure 15 indicate vertical vortex diffusion, by shifting the centroid of vorticity upward, can result in vortex roll up near the tip of the winglet. The vortex, once formed, moves laterally over the ground at a height substantially above that of the baseline vortex (for a distance of about thirty-five semispans behind the airplane for case presented here). To investigate the manner in which this effect may reduce vortex entrainment of spray droplets, single-nozzle deposition tests were conducted using the recently developed dispersal test methods. Results, presented in Figure 16, indicate that the winglets substantially reduce lateral displacement of deposition that results from spanwise vortex flow. Test particles scaled to droplets sufficiently large that they are unlikely to become entrained (water droplets, dia. 371 microns) were used in these tests since methods are not yet developed at the facility to measure amount of material in the vortex.

These test results are interpreted to indicate a reduced tendency for spray droplets to become entrained in the vortex, with winglets installed, since the influence of the vortex on larger particles is clearly shown to be reduced. It is not yet certain that this method of reducing entrainment will result in improved drift control, however, since material which is entrained with winglets installed, although reduced in amount, may be lifted higher and be more greatly influenced by adverse meteorological conditions, such as crosswinds. Flight deposition tests will be required to resolve such uncertainties. Results to date though limited, are promising because they demonstrate that wake properties can be tailored aerodynamically to produce changes in deposition.

Research in Full Scale Wind Tunnel

Objectives and Approach

In the 9x18 meter Full Scale Wind Tunnel, full-scale agricultural aircraft and dispersal systems for both liquid and solid applications are tested. The overall objective of these tests is to obtain baseline data on current technology to be used in analysis to improve aircraft aerodynamics and dispersal system efficiency. Tests have recently been conducted on a Thrush Commander 800, shown mounted in the tunnel test section in Figure 17. This test program was broad in scope, with the aircraft aerodynamics phase including performance, and stability and control tests, and evaluations of a number of modifications designed to provide overall system improvement, such as leading-edge slats, ring cowling, wing-fuselage and canopy fairings, and wake modification devices. Tests were made on the airplane alone, and with dispersal systems installed on the airplane. A detailed discussion of the aerodynamics test phase is beyond the scope of the present paper; emphasis here is placed on dispersal systems research.

Research on Dispersal Systems

In the dispersal systems phase of tests, the various systems were operated, or such operation was simulated, to evaluate performance and efficiency. With dry material spreaders, pressure surveys were made to evaluate internal flow characteristics with and without perforated blockage plates to simulate internal material transport. Conventional and advanced dry material spreader concepts for improved efficiency were evaluated.

In the liquid dispersal phase a new test technique was evaluated, which allowed documentation of near-field spray characteristics and spray-wake interactions. Spray dispersal systems installed on the airplane were operated and droplet size distributions and number concentrations were measured, in situ, behind the airplane with laser droplet spectrometer probes under simulated flight conditions. The test arrangement, showing droplet probes installed on the tunnel survey rig, is illustrated in Figure 18, and a typical two-dimensional real time video display of droplet size measured with the probes during the tests is shown in the photograph in Figure 19. Droplet measurements in the near-field wake, heretofore unavailable, permit effects of major airframe, dispersal system, and flight variables on spray characteristics to be studied. Effects of nozzle and boom location, and vortex modification devices on near-field spray patterns, for instance, can be measured and correlated with laboratory baseline (wind off) experiments, small-scale model tests, and flight spray deposition tests. Data are also valuable for use as input to wake and particle dynamics computer programs to improve prediction of wake-spray interactions and ground deposition.

Liquid systems representative of a wide range of applications with both pesticides and herbicides were used for spray measurements. These systems, shown in Figure 20, include nozzles designed for improved drift control (disc-core and hypodermic-needle airfoil boom types), and rotary atomizers. Droplet size spectra produced ranged from VMD's (Volume Median Diameter; based on static "wind off" manufacturer's data) less than 100 μm to VMD = 1000 μm. The rotary atomizer was tested at two blade settings to produce drop VMD's from about 100 to 300 μm, a size range used primarily for forest pesticides and low-volume low-toxicity chemicals. The side entrance nozzles produce a hollow-cone spray pattern and were tested with two size orifices to produce drop VMD's from about 340 to 470 μm, a range of drop sizes commonly used for low-toxicity agricultural chemicals where good coverage is necessary. The disc-core drift reduction nozzles, which also produce a hollow-cone pattern, and hypodermic-needle airfoil type nozzles were tested to produce drops around 1000 μm, a size recommended for toxic, restricted herbicides (ref.1). The spray pattern with all of these systems was mapped in a two-dimensional array one semispan downstream of the boom location. Although the results have not yet been fully analyzed, the measurements were made successfully, providing confidence in the test technique.

Concluding Remarks

The status of aerial applications technology research in Langley's Vortex Research Facility and Full-Scale Wind Tunnel has been described. Efforts to date have been directed mainly toward developing and validating the required experimental and theoretical research tools. In the Vortex Research Facility, a capability to simulate aerial dispersal of materials from agricultural airplanes with small scale models and numerical methods has been developed and demonstrated. Exploratory tests on wake modification concepts have demonstrated the feasibility of tailoring wake properties aerodynamically to produce favorable changes in deposition.

In the Full-Scale Wind Tunnel an aerodynamic evaluation of the Thrush Commander 800 agricultural airplane with various dispersal systems installed has been conducted. A number of modifications designed to provide overall system improvement to both airplane and dispersal system were examined, and a new test technique to document near-field spray characteristics was evaluated.

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Figure 1.- Thrush Commander agricultural airplane.

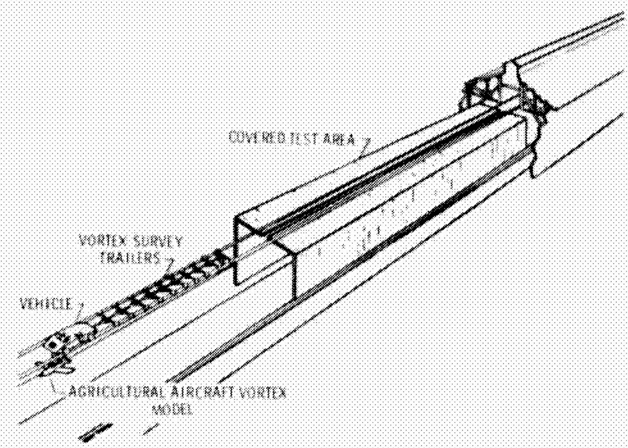

Figure 4.- Sketch of the Langley Vortex Research Facility.

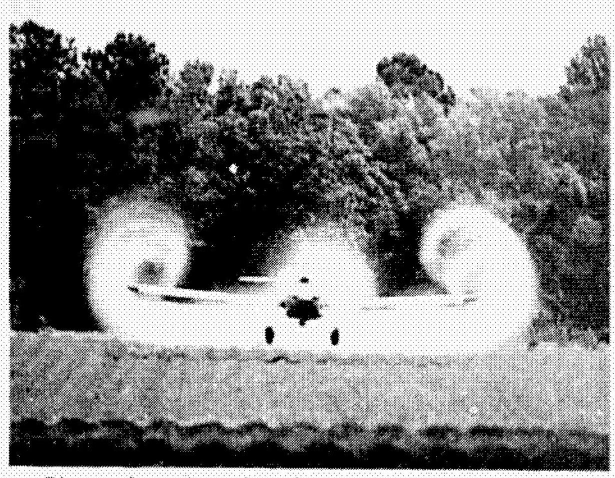

Figure 2.- Example of spray-wake interaction.

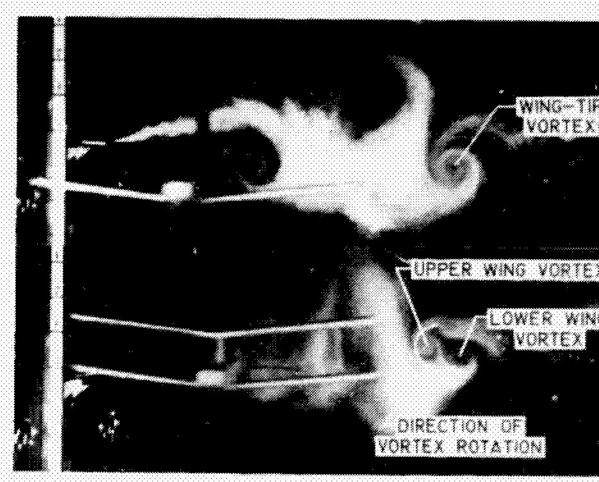

Figure 5.- Flow visualization of wake vortex systems of monoplane and biplane.

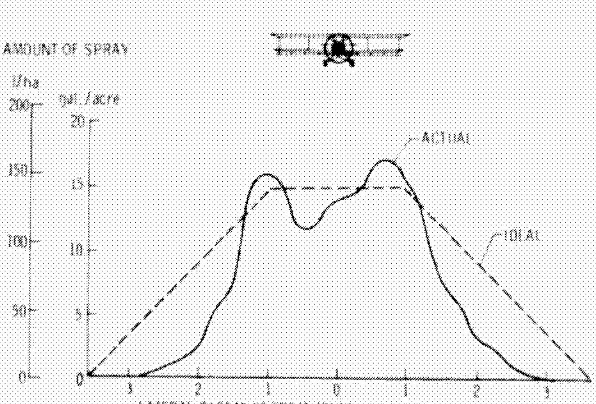

Figure 3.- Effect of interaction on deposition pattern.

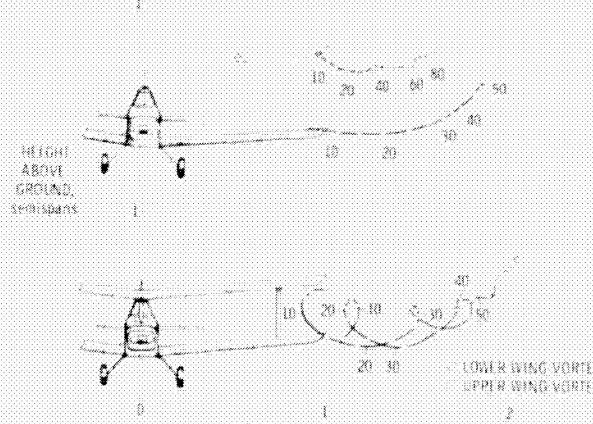

Figure 6.- Vortex lateral transport of monoplane and biplane in ground effect. Ticks on curves indicate downstream distance in wing semispans.

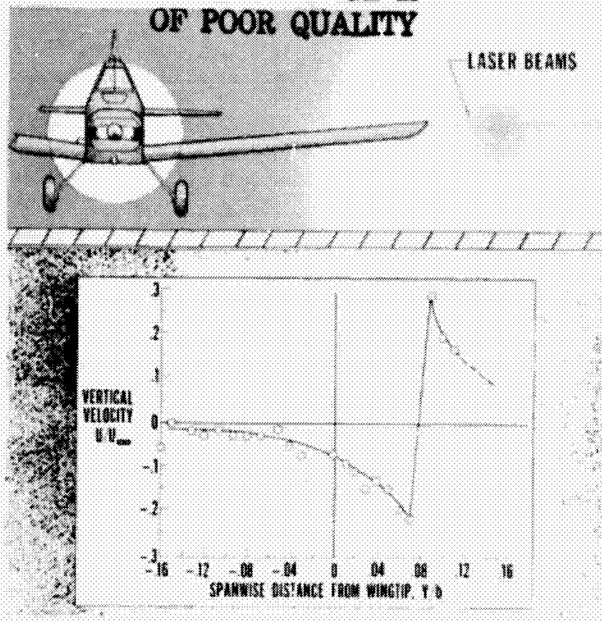

Figure 7.- Laser doppler velocimeter measurement of wake vortices.

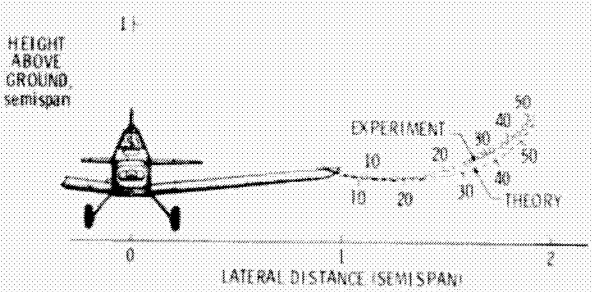

Figure 8.- Comparison of computed and measured vortex paths in ground effect.

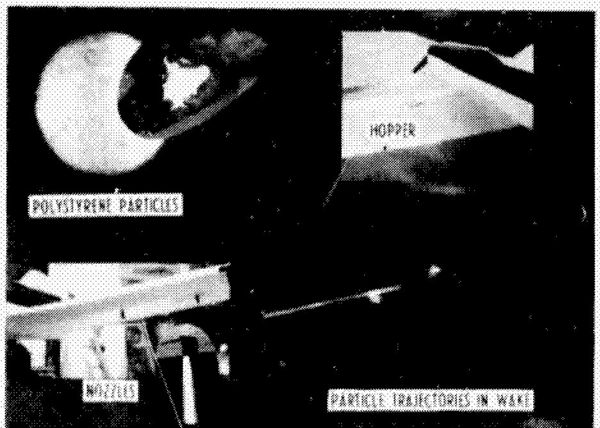

Figure 9.- Dispersal of scaled particles from model airplane and measurements of particle trajectories in model wake.

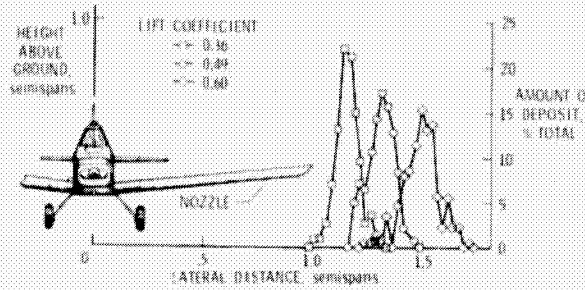

Figure 10.- Effect of variation in airplane lift coefficient on lateral displacement of single-nozzle deposition pattern. Nozzle at 0.75 b/2.

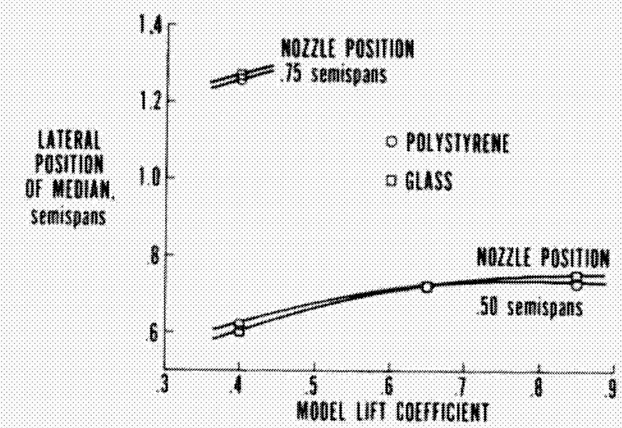

Figure 11.- Comparison of lateral position of median of single-nozzle deposition patterns with polystyrene and glass test particles.

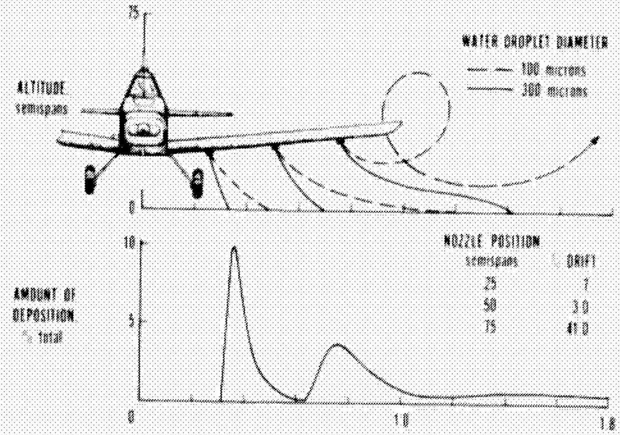

Figure 12.- Calculated particle trajectories and deposition patterns.

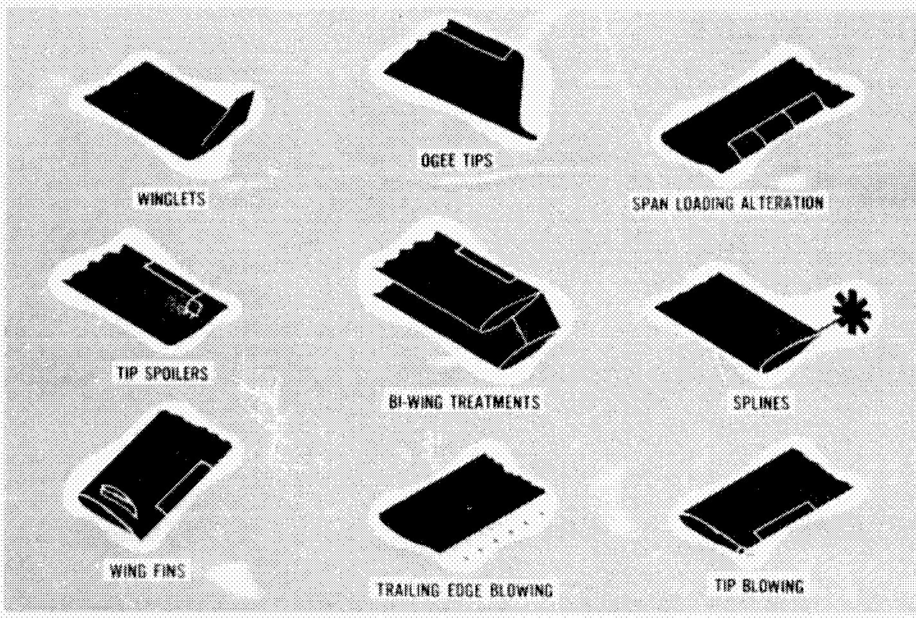

Figure 13.- Candidate wing treatments for wake modification of agricultural airplanes.

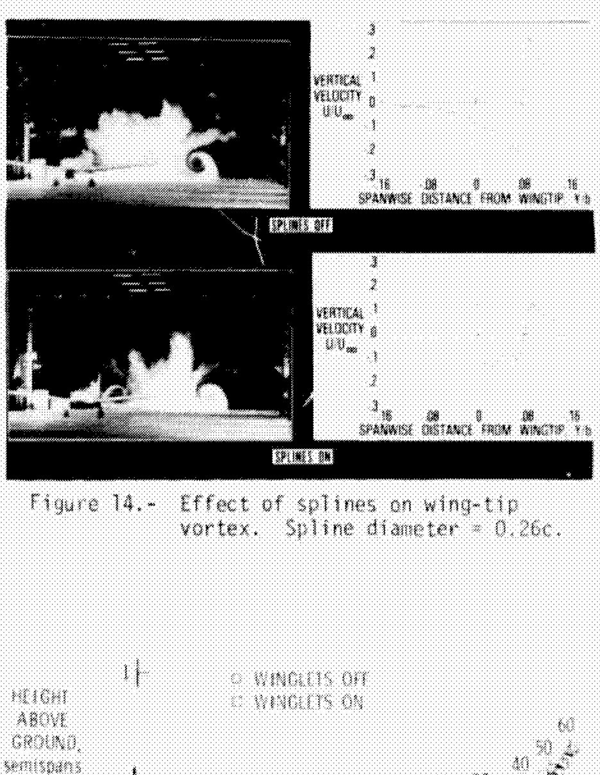

Figure 14.- Effect of splines on wing-tip vortex. Spline diameter = 0.26c.

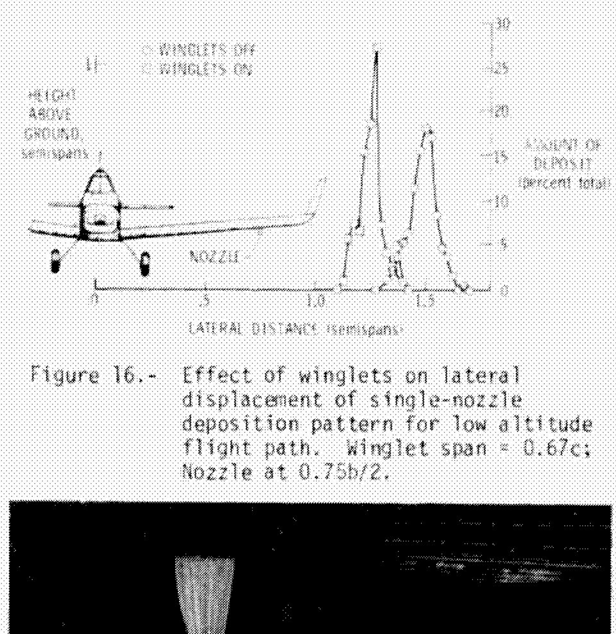

Figure 16.- Effect of winglets on lateral displacement of single-nozzle deposition pattern for low altitude flight path. Winglet span = 0.67c; Nozzle at 0.75b/2.

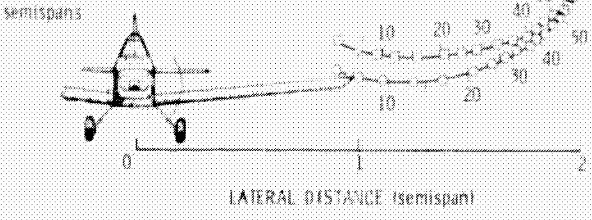

Figure 15.- Effect of winglets on lateral transport of vortex in ground effect. Winglet span = 0.67c.

Figure 17.- Thrush Commander agricultural airplane in test section of Full-Scale Wind Tunnel.

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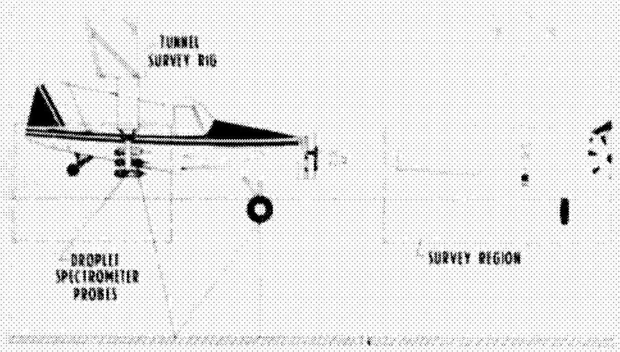

Figure 18.- Test setup for wind tunnel measurement of spray characteristics behind agricultural airplanes.

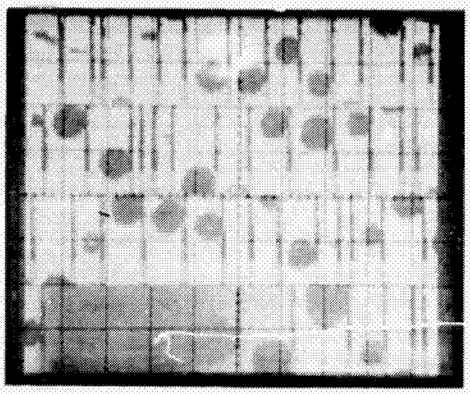

Figure 19.- Droplet image display.

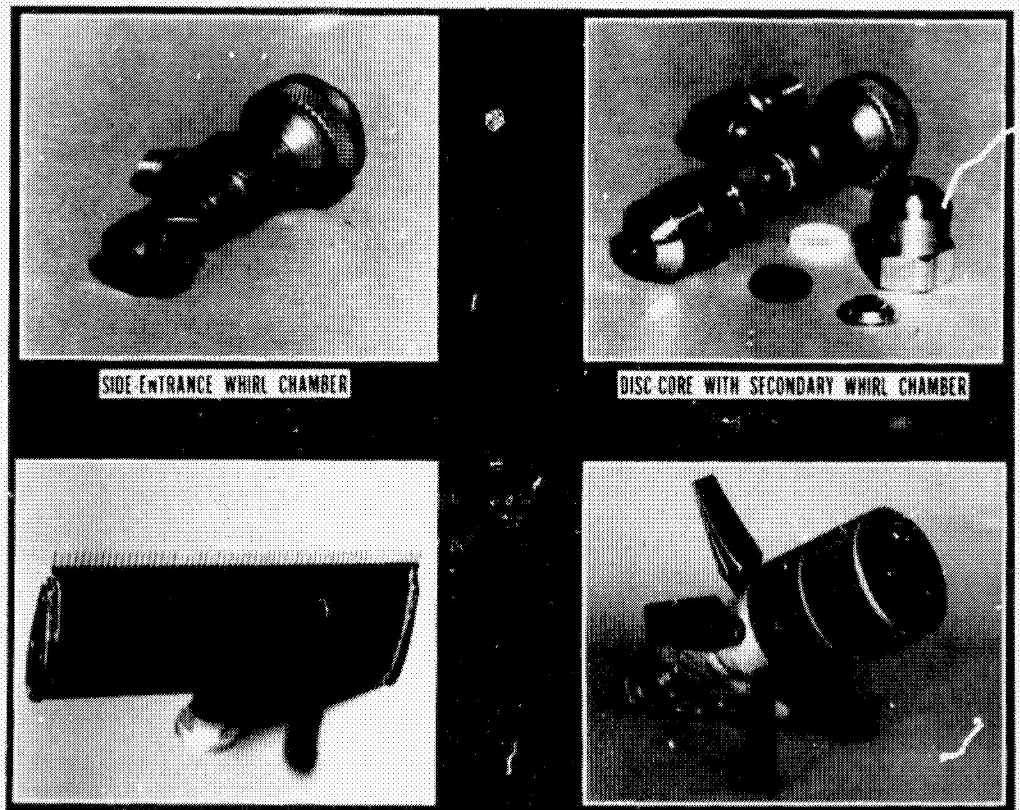

Figure 20.- Types of spray nozzles and atomizers tested on airplane in wind tunnel.

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16 Abstract

The Langley Research Center of the National Aeronautics and Space Administration is currently engaged in basic research to improve aerial applications technology. As part of this program, Langley's Vortex Research Facility and Full-Scale Wind Tunnel play lead roles in aircraft systems research to improve aircraft aerodynamics and dispersal systems efficiency, and in studies of aircraft wake-dispersal interactions to improve drift control and dispersal transport.

In the Vortex Research Facility, small-scale models of agricultural airplanes are tested and numerical methods are utilized to study interactions between the airplane wake and the dispersed spray and granular materials. Methods are being developed to measure and predict dispersal transport and ground deposition with the objective of modifying wake characteristics and dispersal techniques to obtain interactions more favorable to wide, uniform deposition patterns and reduced drift. In the Full-Scale Wind Tunnel, full-scale agricultural airplanes and dispersal systems for both liquid and solid applications are evaluated to improve aircraft aerodynamics and dispersal systems efficiency. This paper presents the program status in these two facilities with emphasis on wake interactions and dispersal systems research.

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