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A SUMMARY OF NASA RESEARCH ON EFFECTS OF HEAVY RAIN ON AIRFOILS

by

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SUMMARY

This paper presents results from a broad National Aeronautics and Space Administration (NASA) research program to obtain fundamental aerodynamic information regarding the effect of heavy rain on airplane performance. The take-off and landing characteristics are of particular concern, and the aim of the program is to understand the physical phenomena associated with any aero-dynamic performance penalty that may occur during a rain encounter. This over-view includes results of recent attempts to measure high-intensity, short-duration rainfall, a discussion of some of the earlier analytical investigations of rain effects on airfoils, a review of some promising experimental methods for evaluating rain effects, and some important scaling considerations for extrapolating model data.

Based on the comparisons available between the limited large-scale results and the wind-tunnel results, rain scale effects are not large and wind-tunnel results can be used to predict large-scale heavy rain effects. Although reductions in maximum lift capability and corresponding increases in drag were measured for both the cruise and high-lift configurations, the high-lift configuration was more sensitive to the rain environment than the cruise configuration. The data indicated a reduction in maximum lift capability with increasing rainfall rate and an associated decrease in the angle of attack at which maximum lift occurs. It would appear that normal transport aircraft operations would not be affected by heavy rain since most operations avoid angles of attack near stall. However, if the heavy rain encounter occurs during a severe low altitude wind shear then the piloting procedures used to counter the wind shear effects may result in operating at a higher than normal angle of attack.

NOMENCLATURE

C_d	section drag coefficient
C_D	drag coefficient
C_l	section lift coefficient
C_L	lift coefficient
LWC	liquid water content, g/m^3
R	rainfall rate in/hr or mm/hr
α	angle of attack, deg.

INTRODUCTION

Until the late seventies the recognition of weather-related safety hazards to aircraft performance and operations had included clear-air turbulence, lightning, icing, hail, low-altitude windshear, and microburst. The latter two phenomena have long been recognized as hazards to aircraft landing and take-off operations. In 1977 the United States Federal Aviation Administration (FAA) conducted a study of 25 aircraft acci-dents and incidents which occurred between 1964 and 1976 in which low-altitude wind shear could have been a contributing factor (ref. 1). Of the 25 cases (23 approach or landing and 2 take-off) in the study, ten cases had occurred in a rain environment, and in five cases these were classified as intense or heavy rain encounters. These results led to the reconsideration of high-intensity, short-duration rainfall as a potential weather-related aircraft safety hazard, particularly in the take-off and/or approach phases of flight.

This paper is an overview of the most recent work conducted by the NASA and others to study the potential influence of heavy rain on airfoil performance. The overview includes results of recent attempts to measure high-intensity, short-duration rainfall, a discussion of some of the earlier analytical investigations of rain effects on airfoils, a review of some promising experimental methods for evaluating rain effects, and some important scaling considerations for extrapolating model data. The latest experimental data are also presented and discussed. A complete understanding of the influence of rain on airfoil performance will require significant additional effort both analytically and experimentally before an assessment of the degree of hazard associated with flight operations in a rain environment can be made.

THE CHARACTERISTICS OF HEAVY RAIN

In order to develop analytical models and conduct experimental studies on the effect of rain on airfoil performance, the phenomenon of naturally occuring precipitation needs to be understood. An understanding of the drop size distribution associated with heavy rain, the frequency of occurrence, and the range of rainfall rates is required in order to assess hazard potential for aircraft operation.

Two "lump parameter" quantities generally used to describe rain are rainfall rate (R) and liquid water content (LWC). Rainfall rate is the linear accumulation depth at ground level per unit time and is typically used to characterize rainfall at ground level. For airborne measurements the liquid water content, the mass of liquid water per unit volume usually expressed as g/m^3, is the meaningful parameter. The relationship between LWC and R is uniquely dependent on the type of storm and the intensity level of the storm. In the absence of a vertical wind velocity, the LWC is directly related to the rainfall rate and the drop size distribution. Figure 1 from Dunham, ref. 2, is a plot of the LWC as a function of rainfall rate for both light widespread rain and thunderstorm type rain. Rain is adequately modeled when the type of rain environment is specified (thunderstorm or continous) and either the liquid water content or rainfall rate is given.

The range of rainfall rates that an airplane could expect to encounter varies from light rain of 5-10 mm per hour up to very large rainfall rates. The ground-level world record rainfall accumulation of 1.23 inches in one minute was measured in an intense afternoon thunderstorm on July 4, 1956, (ref. 3). The volume of rain accumulated in the one minute time interval is equivalent to a rainfall rate of 1830 mm/hr (73.8 in/hr). The upper boundary for airborne measurements of liquid water content is 44 g/m^3, corresponding to approximately 2920 mm/hr (117 in/hr), measured by an instrmented F-100 airplane in 1962 by Roys and Kessler (ref. 4).

With the resurgence of interest in the characterization of high-intensity rain-fall, a review of the literature prior to 1987 pertaining to natural rainfall measurements revealed that the majority of the ground-based rainfall database was averaged over relatively long time constants using a weighing-bucket, more commonly referred to as a tipping bucket (Jones and Sims, ref. 5). According to Melson (ref. 6), this measurement technique results in lower rainfall rates being calculated and masks the short-duration, high-intensity rainfall characteristics associated with thunder-storms. The work of Jones and Sims and Melson both address the magnitude, duration and probability distribution of high-intensity rainfall.

The probability distribution data collected by Jones and Sims, measured over time constants of 1- and 4-minute accumulations at ground level, are useful for determining the potential for encountering a given rainfall rate. They analyzed data collected over a one-year period on recording weighing-bucket raingages placed throughout the world. Gages from maritime subtropical (Southeastern USA, Vietnam, Marshall Islands, Japan), continental temperate (Midwestern USA, Alaska), maritime temperate (England, France, West Germany, Northwestern USA), and midlatitude interior (Israel, Southwestern USA) regions were used. Figure 2 is a summary of the averaged zonal frequency distribution curves obtained. The probable number of minutes a given rainfall rate (or greater) can be expected in a given climatological zone can be obtained from figure 2 by converting the ordinate from percent to a fractional portion of time and multiplying by the number of minutes in a year (5.2596×10^5). The Jones and Sims data indicate that for about two minutes every year in the maritime suptropical zone, a rainfall rate greater than 200 mm/hr (8 in/hr) could be expected at any location.

The lack of rainfall measurements over very short time constants, on the order of seconds, led to the development of a ground-based natural rainfall measurement technique by Melson. His technique acquires data over very short time constants, as short as one sample per second. Data are being acquired at 6 geographical sites: Darwin, Australia; Seattle, Washington; Denver, Colorado; Kennedy Space Center, Florida; Hampton, Virginia; and Wallops Island, Virginia. His measurement technique has verified the existence of high-intensity rainfall at ground level (ref. 7). Figure 3 is a bar chart summary of the frequency and magnitude of the events measured above 100 mm/hr (4 in/hr) and the duration times of those events. Over 7,000 events have been measured above 100 mm/hr since the test program began in 1988. The maximum rainfall rate measured of 720 mm/hr (28 in/hr) occurred for just under ten seconds at NASA Wallops Flight Facility in 1990. In figure 4 the data are presented as percentages of the total number of measurements indicating that one quarter percent of the events measured were above 20 in/hr. The rainfall rates above 20 in/hr were sustained up to 10 seconds per event. These ground-based results along with the inflight thunderstorm measurements by Roys and Kessler indicate that the probability of an airplane encountering short-duration rainfall rates greater than 200 mm/hr (8 in/hr) may be higher than the probability indicated by Jones and Sims.

ANALYTICAL WORK

The effect of rain on the aerodynamic performance of an airplane was addressed analytically as early as 1941 by Rhode (ref. 8). His analysis indicated that drag increases associated with the momentum of a DC-3 aircraft encountering a rain cloud with a water mass concentration of 50 g/m^3 (equivalent to approximately 1270 mm/hr or 50 in/hr) would cause an 18 percent reduction in airspeed. Rhode considered such an encounter to be of a short duration and of little consequence to an aircraft flying at 5000 feet.

Since low visibility take-offs and landings were not routine in 1941, the consequences of a heavy rain encounter during these phases of flight was not considered. However, for a modern day transport such an airspeed loss during take-off or landing would be significant. The influence of rain on airplane performance was addressed again in 1982 when Haines and Luers (ref. 9), under contract from NASA, evaluated the effect of rain on aircraft landing performance. In the intervening years a great deal of work had gone into calculating the motion of water drop particles in the flowfield about an airfoil (refs. 10 to 14); however these efforts were directed at calculating water drop trajectories and impingement on the airfoil for purposes of estimating ice accretion. The influence of liquid water on the airfoil performance was not calculated.

The Haines and Luers study was an attempt at refining the study of Rhode to estimate the effects of rain on a modern-day airplane. Their analysis not only included the calculation of the impact momentum of the raindrops, but also estimated the increase in skin friction drag by equating the water layer waviness and raindrop crater effects on the airfoil surface to an equivalent sand grain roughness. Using empirical data for roughness effects on airfoil lift they calculated the rain effect on the lift and drag of a 747 transport. Their analysis estimated a 2 to 5 percent increase in drag and a 7 to 29 percent reduction in maximum lift with associated reductions in stall angle from 1 to 5 degrees for rainfall rates from 100 to 1000 mm/hr (3.94 to 39.37 in/hr). These predictions, of course, constitute a substantial loss of performance.

In 1984 Calarese and Hankey (ref. 15) studied droplet drag acting as a body force in the Navier-Stokes equations. This analysis neglects the interface effects of droplet splashing, cratering, and water-layer formation. Their analysis produced a pressure distribution for an NACA 0012 airfoil for the limiting cases of a very fine rain (small drop size and a drop Reynolds number much less than 1) and for a coarse rain (large drop size and large Reynolds number). For the coarse rain little change in airfoil pressure distribution was noted. For the fine rain, significant changes in pressures were predicted which showed a small increase in lift with increasing water spray concentration.

In 1985, Kisielewski (ref 16) performed a three-dimensional Euler analysis to investigate the effects of momentum and energy exchange between the rain and the flowfield. He concluded that the rain had little effect on the calculated lift produced by a simple airfoil. Both Calarese and Hankey and Kisielewski concluded that the major influence of rain on airfoil performance was probably dominated by viscous effects of the water droplet splashing and its subsequent interaction with the air boundary layer, but these effects were not modeled in their analyses.

EXPERIMENTAL METHODS

The experimental investigation of rain effects on the aerodynamics of airfoils is a technical challenge as difficult as investigating the effects analytically. A full-scale flight test investigation would require that performance measurements be made on an airplane while in a severe rainstorm. In addition to the hazard to the test pilot, extraction of accurate performance measurements and environmental parameters would be very difficult. Because of the variability of natural rain, repeatable conditions would be difficult if not impossible to obtain.

Scale model tests of the effects of rain present a different set of challenges in that they require the simulation of properly scaled rain conditions. The three types of tests which have been used for investigating the effects of rain are (1) a rotating arm in which a model is placed at the end of a counterbalanced rotating beam, (2) conventional wind tunnels, and (3) a track in which the model is propelled down a straight track segment.

Rotating arm facilities have been quite useful for studying single-drop impact dynamics (refs. 17 and 18). Airfoil performance measurements have not been attempted with the rotating arm facility because the centrifugal effects on the water film would influence the results. Wind tunnels and track facilities are considered to be the best methods of obtaining airfoil performance data, and in both methods the technique for simulating rain and developing scaling relationships presents the areas of greatest difficulty. For the wind tunnel the difficulty lies in obtaining a uniform distribution of the water with a minimum of influence on the tunnel flow conditions. For the track the water manifolding and nozzle distribution becomes elaborate and extensive in order to cover the test area.

Wind-tunnel testing

In 1985, Bilanin (ref. 19) addressed the subject of scaling for model tests of airfoils in simulated rain. His analysis showed that the the scaling parameters which control the aerodynamic force generated by an airfoil immersed in a rain environment are the following: Reynolds number based on air; Reynolds number based on water; the Weber number; the ratio of mean droplet diameter to model chord; the ratio of the density of air to the density of water; and the angle of attack. The Weber number (We) is the ratio of inertial forces to surface tension forces and is a function of the density of water, drop velocity, volumetric mean drop diameter (the diameter at which half the volume of water is in larger or smaller drops) and the surface tension interactions between water and air. The sensitivity of the aerodynamic characteristics of an airfoil immersed in a rainstorm to each of the aforementioned parameters must be assessed to determine adequate modeling of heavy rain in the wind tunnel.

NASA has developed test techniques and procedures and conducted a series of wind-tunnel tests in the NASA Langley 14- by 22-Foot Subsonic Tunnel. The tests were conducted in the closed test section with dimensions of 14.5 feet high by 21.75 feet wide by 50 feet long. A photograph of a typical test set-up and a schematic of the test technique developed are shown in figures 5 and 6. The model hardware was located in the aft bay of the test section aligned laterally with the tunnel centerline.

The water spray distribution manifold, shown in figure 7, was located approximately 10 wing chord-lengths upstream of the model location and directed the spray horizontally at the model while aerodynamic force measurements were obtained. The shape and location of the spray manifold were selected to minimize the interference effect on tunnel freestream conditions and to allow time for the stabilization of the accelerating water droplets. The manifold was aligned approximately 6 inches above the chord plane of the model to account for gravity effects on the water droplets. Comparisons of model aerodynamic data in and out of the simulated rain environment were made with the spray manifold in position at all times.

The wind-tunnel rainfield simulated a thunderstorm-type rain and was quantified in terms of LWC, drop size distribution and drop velocity. An extensive experimental research effort was carried out by the Jet Propulsion Laboratory (JPL), under contract to NASA, to develop a nozzle design which would simulate a range of rainfall intensity levels and a drop size distribution which would include drops 2 mm in size and larger (ref. 20). The JPL designed nozzles, shown in figure 8, consisted of a series of hypodermic tubes arranged circumferentially around a plenum which would provide control over the drop size and rainfall intensity level independently. These nozzles produced LWC values near those which occur naturally in cloudburst conditions.

Exploratory tests were conducted on a wing with a NACA 0012 airfoil section fitted with a simple, full-span trailing-edge flap at at Reynolds Number of 1.7×10^6. (ref. 2) The wind-tunnel rain simulation system used for the NACA 0012 tests produced LWC values ranging from 13 to 22 g/m^3. A 15 percent reduction in the maximum lift capability of both the cruise and landing configurations of the airfoil model were measured in the simulated rain environment independent of the LWC. A sample of the data is shown in figure 9. The exploratory small-scale wind-tunnel results confirmed the existence of a performance penalty in a simulated rain environment.

Following these tests, an investigation was conducted to determine the severity of the rain effect on an airfoil geometry which was representative of typical commercial transport wing sections as a function of rainfall intensity and to explore the importance of surface tension interactions of water as a scaling parameter (ref. 21). The airfoil model was an NACA 64-210 with leading-edge and trailing-edge high-lift devices tested in cruise and landing configurations. The model had a rectangular planform and was supported between two endplates in an attempt to represent a two-dimensional test set-up as shown in figure 10. The basic airfoil chord was 2.5 feet and the span between the endplates was 8 feet. Details of the cruise and landing configurations tested are shown in figure 11. The high-lift devices consisted of a leading-edge slat deflected at a fixed angle of 57° and a trailing-edge double-slotted flap deflected at a fixed angle of 35.75°.

These tests were also conducted in the Langley 14- by 22-Foot Subsonic Tunnel for Reynolds numbers of 1.8×10^6, 2.6×10^6, 3.3×10^6 based on airfoil chord. The rain spray system was modified to provide adequate coverage of the model at higher rainfall rates than previously tested using the JPL nozzles. The improved rain simulation system produced water mass concentrations ranging from 16 to 47 g/m^3. As shown in figure 12, a 25 percent reduction in maximum lift capability with an associated 8° decrease in the angle of attack at which maximum lift occurs was measured for the high-lift configuration at the highest water mass concentration of 46 g/m^3. For this data set the Reynolds number was 2.6×10^6, the Weber number 270, and the drop diameter to wing chord ratio .0018.

In general, the NACA 64-210 data indicated the same trends as the data for the NACA 0012 airfoil model. Both airfoil sections exhibited significant reductions in maximum lift and increases in drag for a given lift condition in the simulated rain environment. The most significant difference between these two airfoil sections was the sensitivity of the NACA 64-210 airfoil section to LWC. As noted previously the NACA 0012 performance losses in the rain environment were not a function of LWC. Although reductions in maximum lift capability and corresponding increases in drag were measured for both the cruise and high-lift configurations of the NACA 64-210 airfoil model, the high-lift configuration was more sensitive to the rain environment than the cruise configuration. The data indicated a reduction in maximum lift capability with increasing water mass concentration and an associated decrease in the angle of attack at which maximum lift occurs.

Campbell and Bezos (ref. 22) conducted a test using a NACA 23015 airfoil section to evaluate the time required for a wing immersed in rain to achieve a steady state condition. They reported that the transition time for the wing to achieve a steady state condition encountering simulated heavy rain to be less than two to three seconds in most cases. These transition times are within the duration times of all the ground-based rainfall measurements reported by Melson.

The NACA 64-210 test results in terms of lift and drag characteristics in and out of the simulated rain environment represent the baseline data which was used in the evaluation of the large-scale rain effects data.

Large-scale Track Testing

In order to determine to first order if there were significant rain scaling effects, the NASA Langley Research Center and the FAA supported the development of a large-scale ground testing capability for evaluating the effect of heavy rain on airfoil lift. Figure 13 is a photograph of the facility which was developed to acquire aerodynamic data on large-scale wing sections immersed in a simulated natural rain environment. A wing section is mounted on a test vehicle and is propelled along a track through a highly-concentrated rain environment. The simulated rain is produced by a series of spray nozzles suspended above the track. This technique provides a more realistic rain simulation than can be produced in a wind tunnel. The test vehicle is propelled into an environment which exemplifies an airplane flying into a rainstorm. The generation of the rain environment in the vertical direction allows the water droplets to achieve the proper droplet size distribution and terminal velocities found in severe rainstorms. The outdoor rain simulation system developed for this investigation produced rainfall conditions from 2 to 40 in/hr.

The details of the design, development, and operation of the NASA Langley Research Center Aircraft Landing Dynamics Facility (ALDF) for large-scale heavy rain effects testing are described in references 23, 24, and 25. Although the ALDF was designed to test full-scale aircraft landing gear at operational velocities on a variety of simulated runway surfaces, its operating characteristics facilitated the conversion to a large-scale aerodynamic performance testing facility with minimal modifications to the test carriage and track test section. The ALDF is composed of three components: a test carriage, a propulsion system and an arrestment system. A high-pressure jet of water is directed into a turning bucket on the back end of the carriage to provide carriage thrust. Once the peak velocity is attained, the carriage coasts the remaining 1800 feet to the arrestment system. The large-scale wing section was mounted above the central open bay area of the carriage 22 feet above the track as shown in figure 14.

The wing section had an NACA 64-210 airfoil section with a rectangular planform and was mounted between circular endplates. The wing is equipped with leading-edge and trailing-edge high-lift devices deployed to simulate a landing configuration (fig. 15). The ALDF wing chord was chosen to be 10 feet, which corresponds to a scaling factor of 4 when compared to the wind-tunnel model chord of 2.5 feet. The wing span was constrained to a width of 13 feet by the model location chosen. The wing surfaces were painted with commercially available aircraft paint to model the wing surface/rain interaction properly. The ALDF wing structure was constructed based on a requirement to sustain high g-loads at launch. The wing angle of attack, which is set prior to launch and remains fixed during a test run, was varied from 7.5° to 19.5° in 2° increments.

The ALDF Rain Simulation System (RSS) is located approximately 800 feet downstream of the propulsion system (fig. 16) and provides uniform simulated rain over an area 30 feet wide, centered over the track, by 500 feet long. The system consists of three commercially manufactured irrigation pipes positioned length-wise along the track in 100-foot sections which are supported at both ends by a structural support frame. One leg of this frame is piping which allows the flow of water to travel from the water/air supply system up to the three irrigation pipes. Feeding off each irrigation pipe is an array of nozzles whose spacing is dependent upon the desired rainfall rate.

Dynamic pressure is measured by a standard aircraft pitot-static tube mounted on a forward extremity of the carriage. In addition to data on the wing and carriage, the measurement of wind speed and direction at the the rain simulation system location are recorded along with temperature and barometric pressure. Because the carriage is decellerating the Reynolds number varies from 11- to 18- X 10^6. The Weber number also varies from 320-510.

The majority of the rain effects data were obtained at the maximum rain rate of 40 in/hr for an angle-of-attack range of 7.5° to 19.5°. For this rain condition the drop size to model chord ratio was .0009. This rain condition was chosen because it closely approximated a previously tested wind-tunnel condition and met one of the test objectives to investigate the significance of scale effects. A photograph of the carriage exiting the 40 in/hr rain condition is shown in figure 17. Aerodynamic data were also obtained for rainfall rates of 9 and 19 in/hr for an angle of attack range of 9.5° to 19.5°. These rain conditions have a much higher probability of occurrence than the 40 in/hr rain intensity as indicated by references 4 and 6.

The time dependent data were averaged to provide a single lift coefficient for each angle of attack. The lift coefficient versus angle of attack data exhibit the same general characteristics as the previous wind-tunnel results. The rain effect is to reduce the maximum achievable lift coefficient and to reduce the angle of attack for stall. The data shown in figure 18 for the airfoil in the rain environment reflects the fact that the wing has stalled prior to 13.5° angle of attack and attained it highest observable lift at 11.5° angle of attack. A reduction of lift capability of at least 15 to 20 percent is reflected in the data shown in figure 18 for the 40 in/hr rain condition.

SCALING CONSIDERATIONS

The large-scale data were needed to ascertain the utility of the wind-tunnel test technique for determining the effect of heavy rain at full-scale conditions. As noted in the work of Bilanin (ref. 19) difficulties arise when attempting to preserve all the scaling parameters during model testing. The functional form of the Reynolds number is linearly dependent on the test velocity; therefore, as the model size is decreased the test velocity must increase to preserve full-scale Reynolds number. Weber number, on the otherhand, varies as the square of the test velocity and, as a result, these two parameters cannot be preserved simultaneously.

Operational difficulties in achieving the desired drop size distribution and rain intensity level in the wind tunnel were also identified. The wind tunnel rain simulation technique developed during the small-scale tests identified an inherent difficulty in producing large size drops typical of natural rain while at the same time achieving the desired rainfall intensity and drop size distribution (ref. 20). When water is injected into a high velocity airstream at a velocity substantially less than the airstream velocity, the larger drops that form shatter and break up into much smaller drops. Although this difficulty can be alleviated by increasing the water injection pressure so that the initial drop velocity approaches the airstream velocity, the resulting rainfall intensity tends to be too high. The small-scale tests indicated that the drop size distribution and the rainfall intensity levels were a function of the nozzle design, the water injection pressure and the airstream velocity.

Determination of rainfall rate using the wind-tunnel test technique was subject to measurement error (ref. 22). In a wind-tunnel environment, LWC is expressed as a function of the spray area, mass flow rate, and the freestream velocity. A flowmeter measured the mass flow rate through the manifold. The spray width and height were photographically obtained at the model location using a fluorescent dye, an ultraviolet strobe light to enhance the photographic qualities of the spray and a nearfield linear length reference. Due to the dynamic nature of water drops, the boundaries of the spray region at any instant in time are not precisely straight lines, therefore an inherent inaccuracy in deriving the spray area by photographic means lies in the possible error involved in subjectively determining the usable spray region boundaries.

Despite the noted difficulties, the wind-tunnel technique appears to provide a valid estimate of the effects of heavy rain at full scale conditions (ref. 26). The lift coefficients predicted for the ALDF large-scale configuration using the wind-tunnel data are shown in figure 19 along with the ALDF large-scale data acquired at the same test conditions. The two sets of data for the dry wing agree quite well. The ALDF lift-curve slope and maximum lift measured show excellent correlation to the wind tunnel predicted lift performance for that condition. There appears to be a reasonable degree of correlation between the two data sets for the 40 in/hr rain condition. An offset exists between the predicted lift-curve slope and the ALDF lift-curve slope in the rain. One can infer from the data shown in figure 19 that the wet wing attains its highest observable lift at approximately the same angle of attack (between 10° and 11.5°).

Comparisons of the angle of attack for maximum lift and of the percent lift loss in the various rainfall conditions in the wind tunnel and at large scale are shown in figures 20 and 21. Based on the comparisons available between the limited large-scale results and the wind-tunnel results, the difficulties in precisely simulating the rain environment in the wind tunnel do not have a first order effect on the impact of the test results. It appears that, to first order, rain scale effects are not large and that wind-tunnel results can be used to predict large-scale heavy rain effects.

CONCLUDING REMARKS

The work described herein is aimed at developing test techniques and tools for providing data which can eventually be used to assess the influence of heavy rain on airplane operations. These analysis methods and test techniques will provide valuable insight into the interpretation of heavy rain effects testing of airplane configurations. The large-scale results are not directly applicable to any airplane configuration but are applicable to understanding and interpreting future wind-tunnel tests.

The preliminary findings of the large-scale testing would seem to support earlier wind-tunnel studies of the effect of very heavy rain on airfoil performance. Extremely heavy rain of 40 in/hr produced a reduction in maximum achievable lift coefficient of at least 15 to 20 percent and an approximate reduction in the angle of attack at which the maximum observed lift occurred of 4° to 6°. Results of these small-scale studies had shown that a two-phase flow environment representing a high-intensity rainfall reduced the maximum lift by as much as 20 percent and increased the drag. Additionally, the stall angle was reduced 4 to 8 degrees in the heavy rain environment. The simulated rain seems to have little influence on the lower angle-of-attack airfoil lift performance characteristics. The severity of the effect is airfoil- and configuration-dependent and is most severe for high-lift configuration airfoils, i.e., leading-edge and trailing-edge devices deployed. Based on the wind-tunnel and large-scale results, it would appear that normal aircraft operations for transport aircraft would not be affected by heavy rain since most operations avoid high angle of attack maneuvers. However, if the heavy rain encounter occurs during a severe low altitude wind shear then the piloting procedures used to counter the wind shear effects may result in operating at a higher than normal angle of attack.

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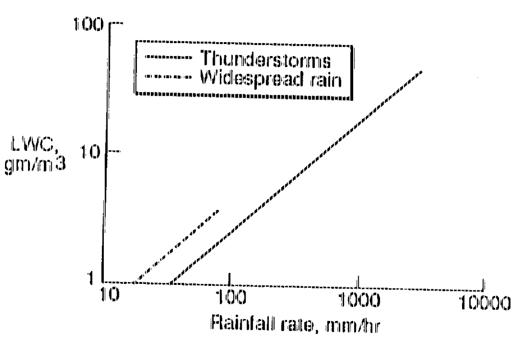

Figure 1 - Liquid water content as a function of rain rate

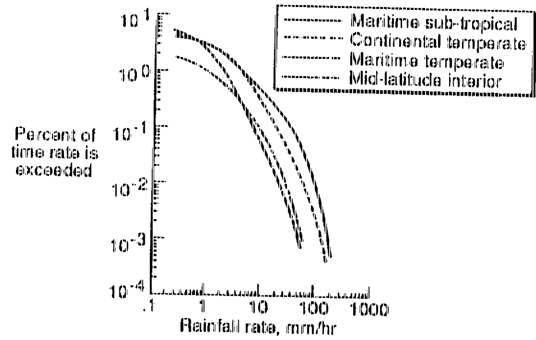

Figure 2 - Climatology of instantaneous Rainfall Rates (as defined by 1 and 4 minute accumulations)

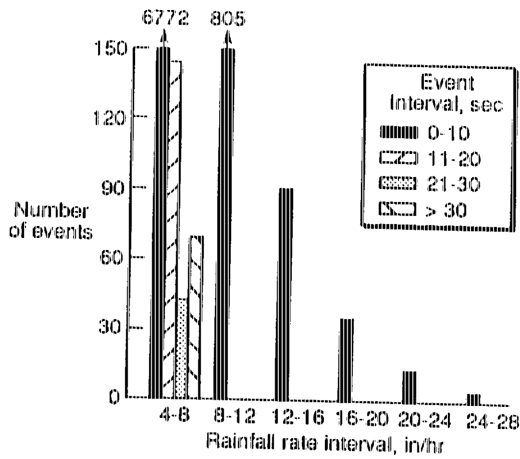

Figure 3 - Short-duration, high-intensity rain rate measurements

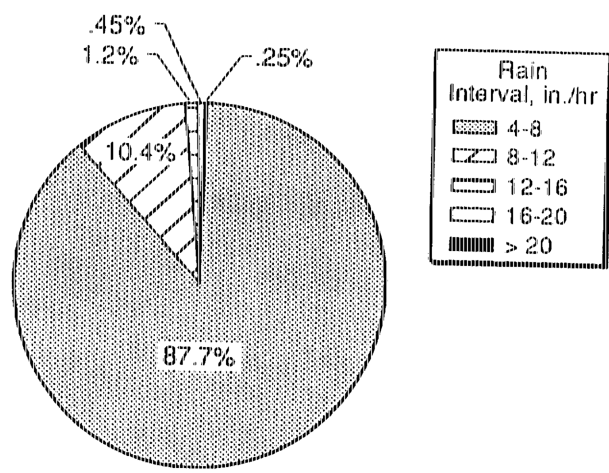

Figure 4 - Distribution of rainfall rates measured for less than 10 secs.

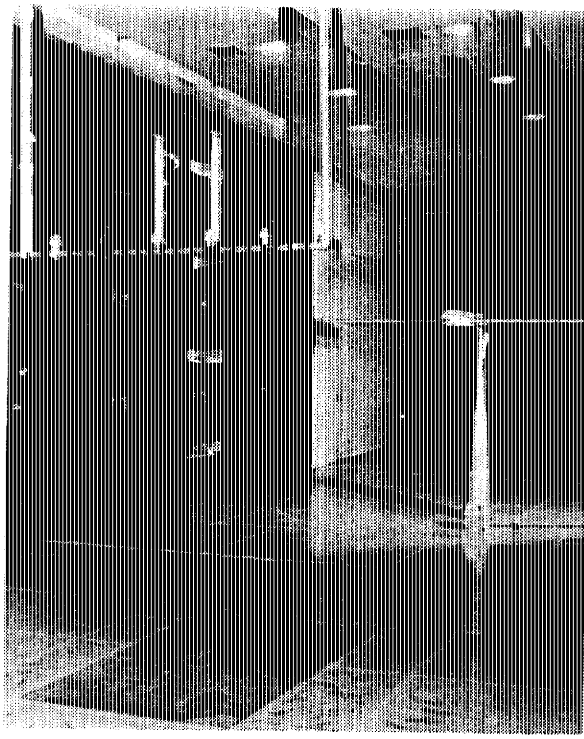

Figure 5 - Rain simulation system mounted in Langley 14- by 22-Foot Subsonic Tunnel

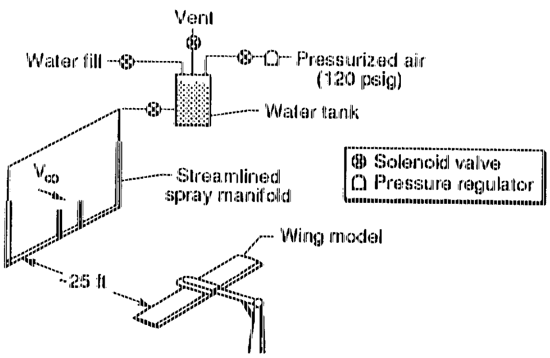

Figure 6 - Typical wind tunnel test set-up for simulated rain effects studies

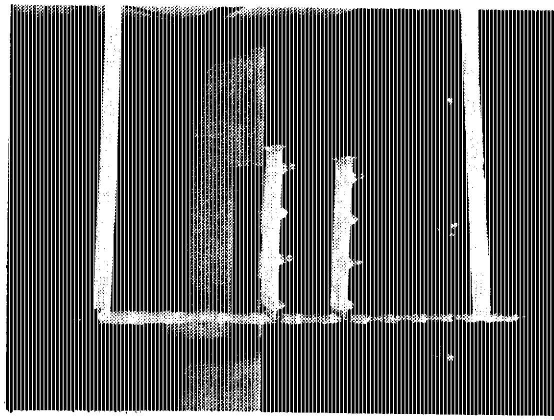

Figure 7 - Close-up detail of nozzle and solenoid arrangement on the spray manifold

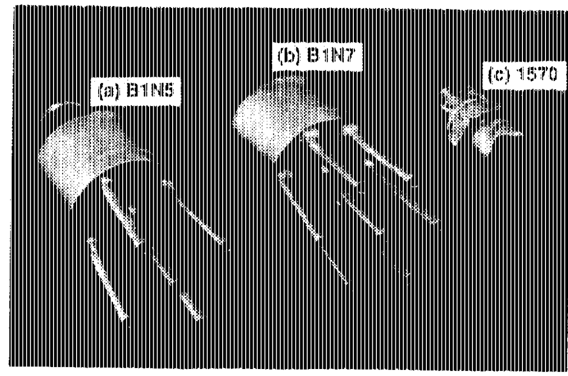

Figure 8 - Three nozzles used to vary the water spray characteristics. From left to right: 5-tube, 7-tube, and commercial nozzle

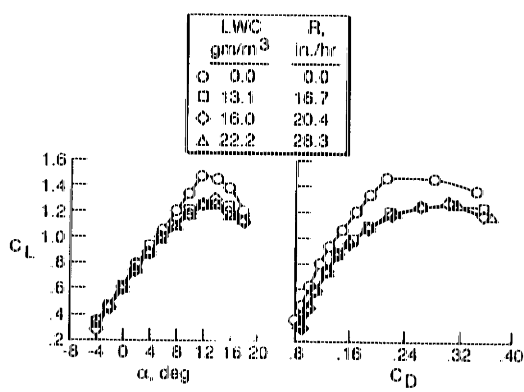

Figure 9 - Lift and drag measurements on a NACA 0012 wing model with a 30% chord flap deflected 20° while subjected to several water spray concentrations

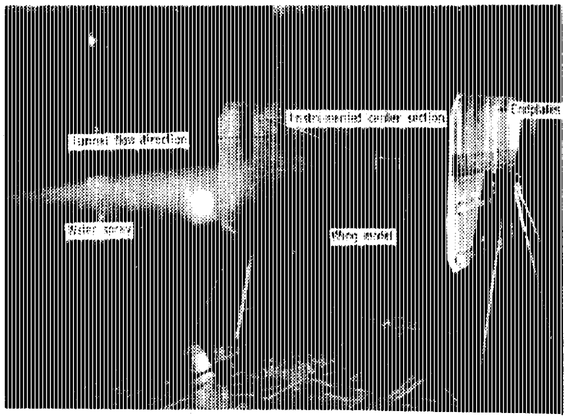

Figure 10 - Photograph of 64-210 model mounted in the wind tunnel

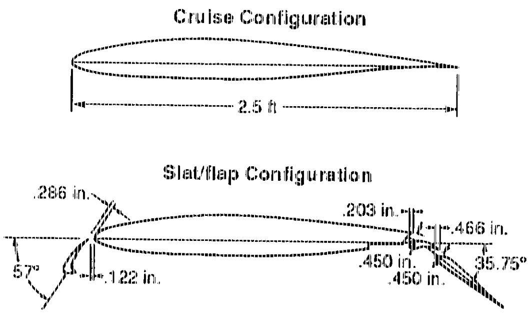

Figure 11 - A cross-section of NACA 64-210 airfoil section

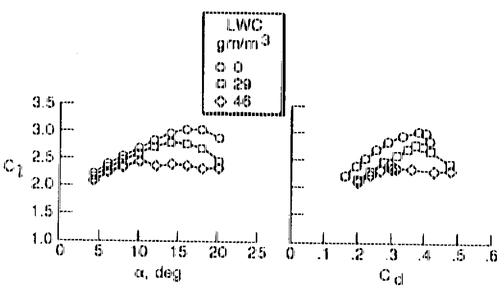

Figure 12 - Effect of rain on NACA 64-210 airfoil with flaps deflected

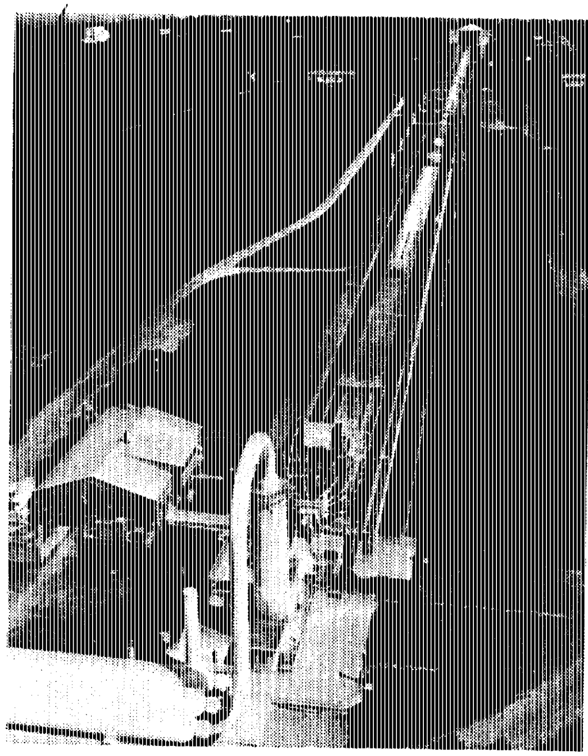

Figure 13 - Aerial photograph of modified Aircraft Landing Dynamics Facility

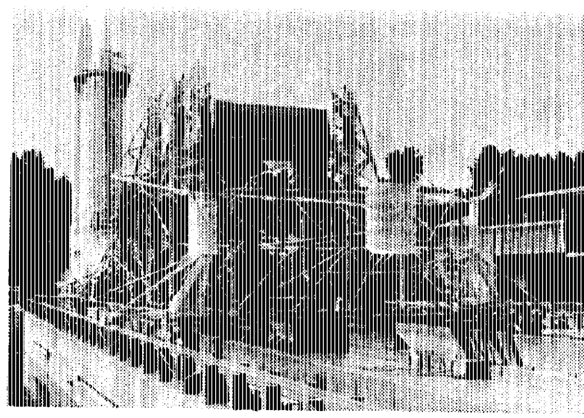

Figure 14 - Photograph of wing mounted on the ALDF carriage

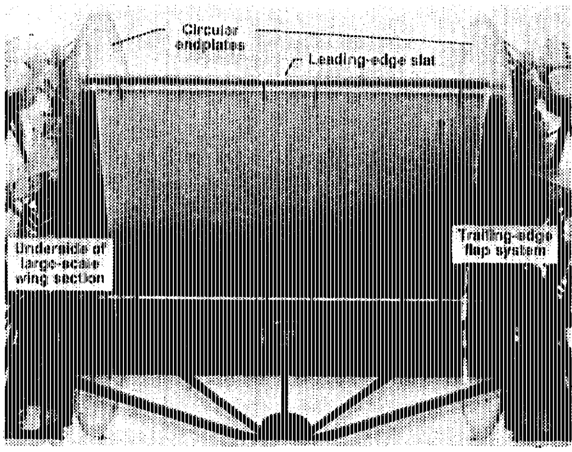

Figure 15 - An underside view of the wing hardware and endplates installed on the ALDF carriage in the high-lift configuration at an angle of attack of 18°

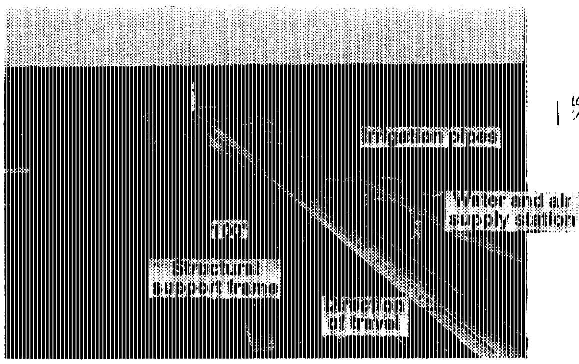

Figure 16 - An aerial view of the ALDF Rain Simulation System

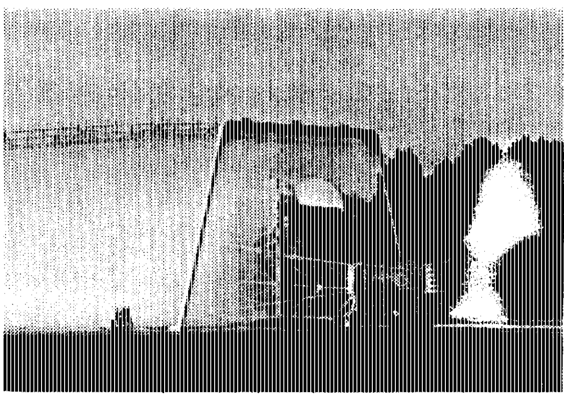

Figure 17 - Carriage exiting from RSS at 40 in/hr rain condition

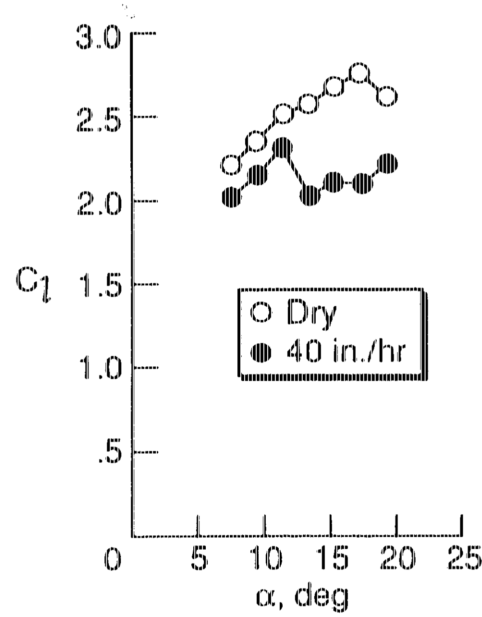

Figure 18 - Lift coefficient from ALDF high-lift data, 160 kts launch speed

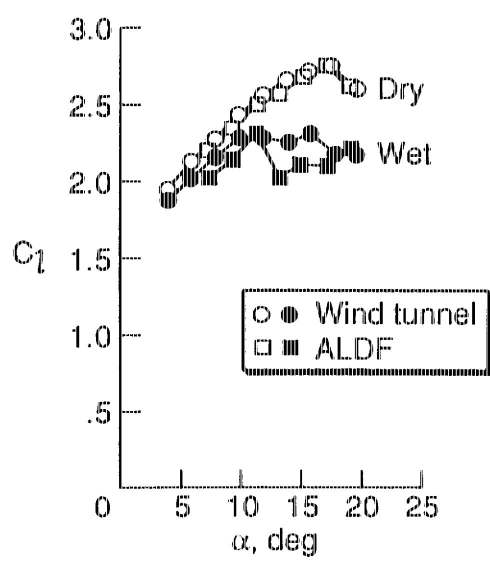

Figure 19 - A ...parison between wind tu... and ALDF data for the h... t configuration

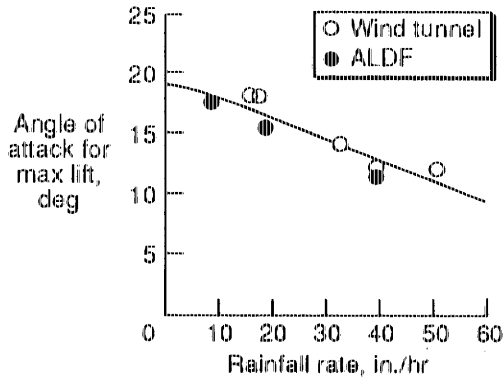

Figure 20 - Rain effect on stall angle of attack

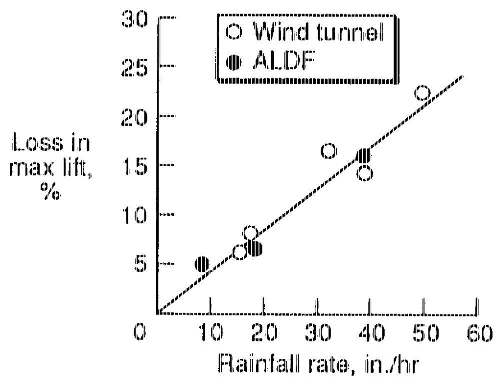

Figure 21 - Rain effect on maximum lift