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PRELIMINARY INVESTIGATION OF EFFECTS OF HEAVY RAIN ON THE PERFORMANCE OF AIRCRAFT

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

¤ **CH-46 and CH-47 composite rotor blade lightning protection testing** HEIDERSCHEIDT, G. SARRO, J. AB(Boeing Vertol Co., Philadelphia, PA) OCT. 1980 8 PAGES American Helicopter Society, National Specialists Meeting on Rotor System Design, Philadelphia, PA, Oct. 22-24, 1980, Paper. 8 p.
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LAST PAGE

SUMMARY

Flight data from the Terminal Configured Vehicle (TCV) B-737 airplane were examined for possible evidence of rain influence on its performance. According to the analysis developed herein, the data was inconclusive, probably due to uncertainty in rainfall rates and duration. There is evidence to support the application of this method of analysis to further investigation.

INTRODUCTION

Due in part to the efforts and theories of James Luers and Patrick Haines (refs. 1 and 2), attention has been focused on the role of heavy rain on the degradation of aircraft performance. However, there is very little experimental evidence to confirm these recent theoretical analyses. In this investigation, data from the Terminal Configured Vehicle (TCV) program's Boeing 737 flights were examined for possible evidence of the influence of rain.

Besides rain, there are other atmospheric factors which can be detrimental to the performance of an aircraft. These include: horizontal wind shears (a change in wind speed and/or direction such as an increase or decrease in head-wind), vertical winds such as updrafts and downdrafts ("downbursts" in the more severe cases), and wind gusts at the phugoid frequency of the aircraft. In the thunderstorm environment where heavy rain is usually encountered, the presence of one or more of the other factors is almost certain. The deterioration of an aircraft's performance will most likely be due to a combination of these quantities. The question of how much rain alone contributes to the deviation in performance may be unanswerable at present. However, the effects from horizontal wind shear, downbursts, "phugoid" gusts, and rain can be distinguished (theoretically, at least) from one another by the sequence of changes and/or direction of change among certain aerodynamic parameters such as angle of attack, pitch angle, and sink rate. That was the approach used in this investigation. When there was a sudden change in performance, the flight data was examined for the signature of the atmospheric phenomena in progress. It was hoped the signature for rain-induced performance penalties would be singular and apparent, justifying positive conclusions about the Luers and Haines theory.

Data from the TCV flights were obtained from the aircraft's navigational computer and the Piloted Aircraft Data System (PADS). The pertinent information was presented numerically and/or graphically.

Comments on the Luers and Haines study appear at the end of this report. A bibliography of books and papers concerning the effects of wind shear and rain on aircraft performance is also included.

SYMBOLS AND ABBREVIATIONS

α = angle of attack, degrees

θ = pitch angle, degrees

γ = flight path angle, degrees

T = fuselage reference line and thrust line

Db = downburst vector

X = relative wind vector

V = resultant relative wind vector with downburst

ALPHA AP = angle of attack vane calibration for approach configuration (landing flaps deflected)

ALPHA CR = angle of attack vane calibration for cruise configuration (no flaps)

HDOT = rate of change of altitude, m/sec

NAFEC = National Aviation Facilities Experimental Center (now FAATC)

NASA = National Aeronautics and Space Administration

NOAA = National Oceanographic and Atmospheric Administration

PADS = Piloted Aircraft Data System

TCV = Terminal Configured Vehicle

ANALYSIS

The basic aerodynamic qualities influenced by meteorological factors are the lift and drag of the aircraft. According to Luers (ref. 2), heavy rain (in excess of 100 mm/hr.) induces a loss of lift and an increase in drag. He attributes this to a water film covering the airfoil and fuselage which is roughened due to cratering of the drops at impact and waves in the film. In addition, horizontal and vertical momentum losses arising from the raindrop impacts with the aircraft result in the extraction of potential and/or kinetic energy from the aircraft. Overall, the major (and most dangerous) consequence of these events (rain, downbursts, etc.) is a sudden loss of altitude. Sink rates of 2,100 feet per minute have been documented in the more severe encounters.

A sudden loss in altitude during level flight is an effect (and the first sign of a downgrade in performance) of either a "phugoid" gust, a horizontal wind shear, a downburst, or rain (assuming no pilot inputs). What is the "signature" of each occurrence?

Gusts at the phugoid.- McCarthy, et.al., (ref. 3) and others have studied and modeled horizontal wind gusts containing energy at the phugoid frequency of particular aircraft. The response of the aircraft to this encounter is a phugoid oscillation where there is a large amplitude variation in altitude, airspeed, and pitch while the angle of attack remains relatively constant.

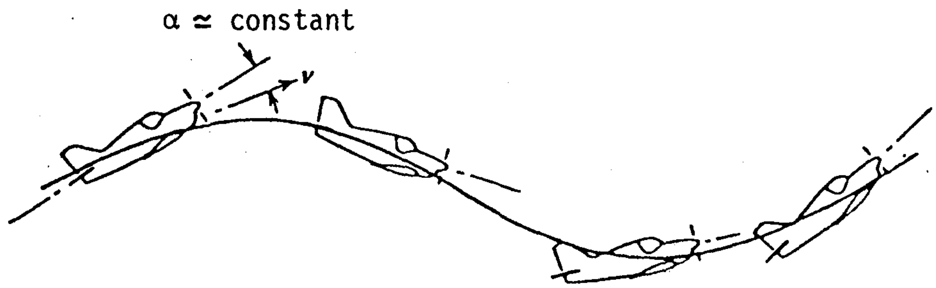


Figure 1.- The phugoid mode; oscillating, longitudinal motion at a constant angle of attack

A computer simulation was performed for a B-727 using available wind data from the Eastern 066 accident (JFK Airport, New York, 1975), and McCarthy determined that the horizontal wind components provided energy precisely at the phugoid frequency. This resulted in a "wave-like" fluctuation of the airspeed from the desired value. He concluded that winds at or near the phugoid can lead to "large excursions in aircraft velocity and altitude ... (which) may result in airspeed oscillations of a nature that would be difficult to control, and in fact, may lead to stall and otherwise disastrous results (especially on landing approach)."

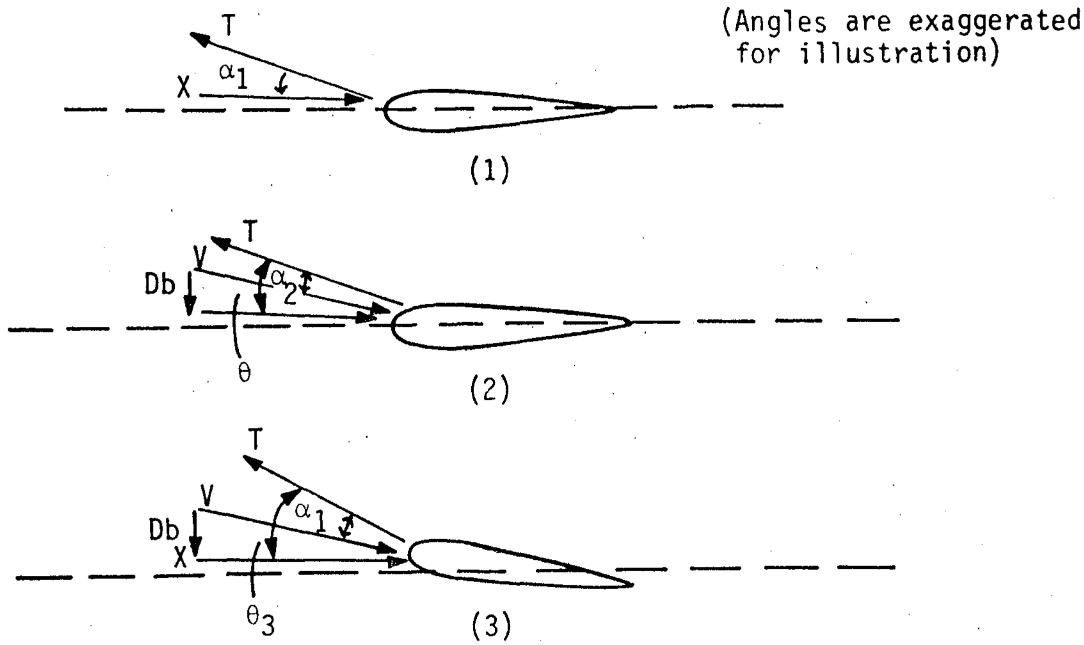
The very nature of the oscillation makes an encounter with a "phugoid" wind easily identifiable in a stick-fixed condition. Flight data will indicate sinusoidal variations in altitude, airspeed, and pitch angle, but almost no change in angle of attack during this interval.

Horizontal wind shear.- A horizontal wind shear exists when changes in wind speed and direction are functions of time and position. A variation in speed of the wind component along the flight path can affect the lift and drag qualities of the aircraft. It will suffice to consider only the headwind in lieu of the longitudinal component since a change in headwind obviously means an inverse change in tailwind. A decrease in strength of the headwind component either from a change in direction or speed or a combination of both by the wind vector will cause the indicated airspeed to decay, but the groundspeed to rise. A sudden loss of headwind causes the indicated airspeed to fall due to the airplane's inertia. Since lift is a function of the square of the airspeed (not groundspeed), an appreciable loss of lift can ensue from a lowered airspeed. Many pilots will confirm "the bottom dropping out" can be severe and without warning.

Normally, airspeed and groundspeed change very slowly with respect to each other. The significant feature of a horizontal wind shear on an aircraft in level flight is: a sudden relative motion between airspeed and groundspeed accompanying a variation in altitude.

Vertical winds.- There are two types of encounters with vertical movements of air. The first involves a descending air mass which envelops the aircraft. This is a downward movement of a sizeable pocket of air. Sink rates of air masses have been measured by Fujita (ref. 4) of up to 135 ft./sec. In such cases, the aircraft's climb capabilities may not be able to overcome the descent. The aircraft attitude instruments may continue to read level flight or even climb (if pilot commanded), but its altitude will be dropping. The aircraft is level (or climbing) in the air mass, but the whole air mass is plunging downward.

Downbursts are sudden and can be of short duration. Their presence is not uncommon at heights of a few hundred feet. This is the reason downbursts are major contributors to takeoff and landing accidents. When a trimmed aircraft in level flight is hit by a downburst, the direction of the relative wind vector changes. The angle of attack is reduced, lift is lost, and the aircraft sinks. The angle of attack is now lower than the trim value, so the aircraft's natural stability pitches it up to regain its previous higher angle of attack and restore trim.



T = thrust line and fuselage reference line
X = relative wind vector in level flight
V = resultant relative wind vector with downburst
θ = pitch angle
α = angle of attach
Db = downburst

(1) Level flight.
(2) Downburst gust is encountered. Aircraft sinks because α_2 is less than α_1.
(3) Natural stability causes aircraft to pitch up, increasing pitch to θ_3, to regain α_1 and restore trim.

Figure 2.- Downburst Effect

Heavy rain.- Detrimental transitions in the lift and drag coefficients of an aircraft by heavy rain can force it to descend. Luers (refs. 2 and 5) has reported an increase in the drag coefficient of 5 to 30 percent based on an increment in the turbulent friction coefficient and a thickening of the boundary layer. Also, a reduction in lift by 30 percent at the higher angles of attack is possible due to premature airflow separation. Assuming no pilot input, the lift-to-drag ratio (L/D) is lowered, causing the flight path to fall below the horizontal (the flight path angle drops to a negative value). This action is necessary so that a component of the aircraft's weight can balance the larger rain-induced drag force while similarly the reduced lift can no longer sustain the total weight but only a component of it. Thus, the relative wind will come from a direction below the aircraft (since rain is considered as the only external agent in this case). The angle of attack is now at a much higher value, causing a further increase in drag. With a rain-roughened airfoil, the lift capabilities are diminished even at a high angle of attack so that the aircraft may not overcome the sink rate which is now further aggravated by a lowered airspeed. The aircraft's natural stability takes over after a short interval and pitches the nose down.

DATA ANALYSIS AND RESULTS

The following is a summary of the data analysis procedure used in this investigation:

(1) Search for sudden losses in altitude.

(2) Check flight controls to be certain it was not caused by pilot input.

(3) Sinusoidal fluctuations in altitude, airspeed, and pitch angle, but a fairly constant angle of attack suggest the responsible phenomena to be a gust at or near the phugoid frequency of the aircraft.

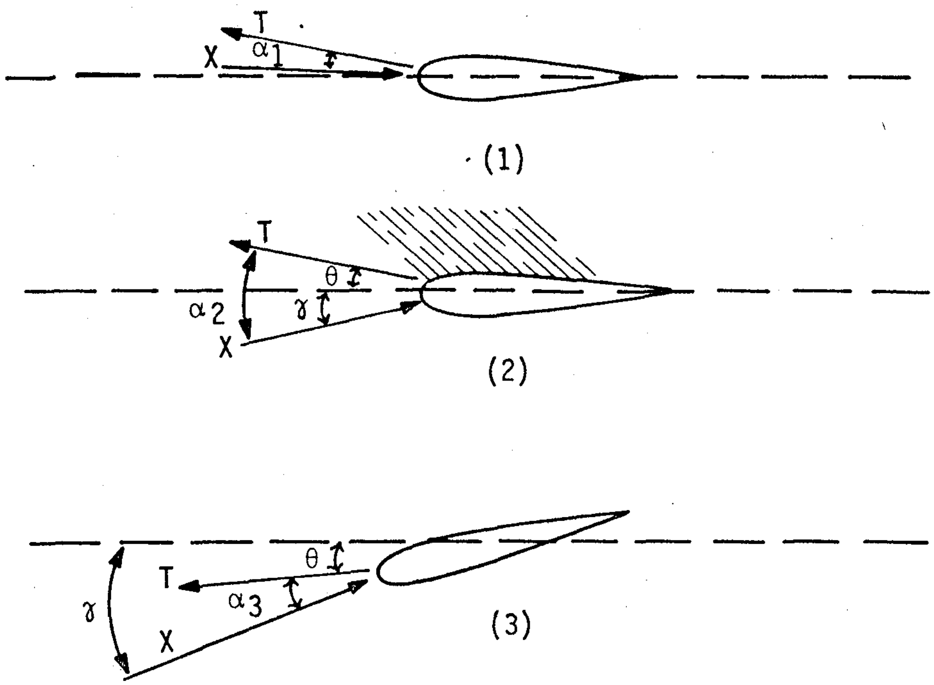
(4) Significant relative motion in indicated airspeed and the groundspeed suggest horizontal wind shear.

(5) Data indicating aircraft is climbing while losing altitude suggests a sinking air mass.

(6) Sudden decrease in angle of attack right before the loss in height followed later by a gradual increase in pitch angle (nose pitching up) suggests downburst.

(7) Sudden increase in angle of attach at start of sink followed by a gradual decrease while the pitch angle decreases (as aircraft pitches nose-down) suggests rain.

TCV personnel suggested a number of flights which may have flown in rain. Weather conditions along the flight routes were traced from NOAA weather maps



(1) Level flight with relative wind, X.

(2) Rain is encountered: aircraft sinks, relative wind increases angle of attack to larger α_2.

Flight path angle, γ, is negative

$$\alpha_2 = \theta + |\gamma|$$

(3) Natural stability causes aircraft to pitch down to smaller angle of attack α_3 to restore trim. Pitch angle, θ, is negative.

$$|\gamma| = |\theta| + \alpha_3$$

Figure 3.- Isolated rain effect

and consultations with the weather stations at Wallops Flight Center, Virginia, and NAFEC, Atlantic City, New Jersey. Flights S-183 (October 13, 1977) and S-219A (March 6, 1978) were the two best candidates for encountering rain.

Over 120 minutes of data from S-183 were analyzed. Time histories and plots of the altitude, flight path angle, true airspeed, ground speed, and wind speed and direction were obtained from the navigation computers; the pitch angle, angle of attack, and vertical speed were obtained from PADS. The procedural guideline stated previously was followed although not necessarily in the given order. Attention was directed to any sudden deviations. Additional information such as thrust and elevator control activity was obtained for intervals in question to ascertain if pilot input was responsible for the deviations.

In general, sudden altitude fluctuations were minimal. The wind data revealed the presence of wind shears which accounted for tendencies in drift angle and cross-track acceleration of the aircraft. Slight relative motion between airspeed and groundspeed were distinguishable, but the wind shears were not strong enough to produce any other significant effects.

The following three pages show some of the relevant parameters at three separate intervals. Figure 4 has the pitch angle, 2 channels for vertical speed (HDOT), and angle of attack in cruise or approach configuration. The "spikes" are not actual data points, but anomalies in the recording. At approximately the 195-200 second mark (noted by arrows) there is a sudden sharp peak in angle of attack. As alpha declines to a lower value, in about 7 seconds, the aircraft begins to sink (negative HDOT). Smoothing out the spikes suggests a decline in pitch to about 1 degree. This behavior matches the characteristics for rain. However, further investigation disclosed the thrust had been decreased (the relative wind comes from below the aircraft, increasing alpha), but it was kept in trim as it descended (relatively small change in pitch angle). This was typical procedure performed in the data reduction.

In figure 5, near the 175 second mark (noted by arrows), there is a sudden increase in angle of attack followed by a sharp increase in HDOT (rise in height). A "smoothing" of the pitch angle suggests a decline from 3 degrees to half a degree after this interval. This is directly opposite of the consequences diagnosed for a downburst. It is logical to conclude that an updraft was experienced. At level flight, an updraft would cause the relative wind vector to come from below the axis of the aircraft. This results in a larger angle of attack which, along with the force of the updraft, lifts the aircraft higher. Its natural stability then pitches the nose down to restore a trimmed configuration. Without pilot input, this is a reasonable and probable explanation of the flight data.

The curves in Figure 6 are indicative of the whole flight: smooth trends with little erratic behavior. Influences in the aircraft from slight wind shears and updraft were apparent in the data at various times. But it is the absence of any major losses of altitude (lift) or significant changes in

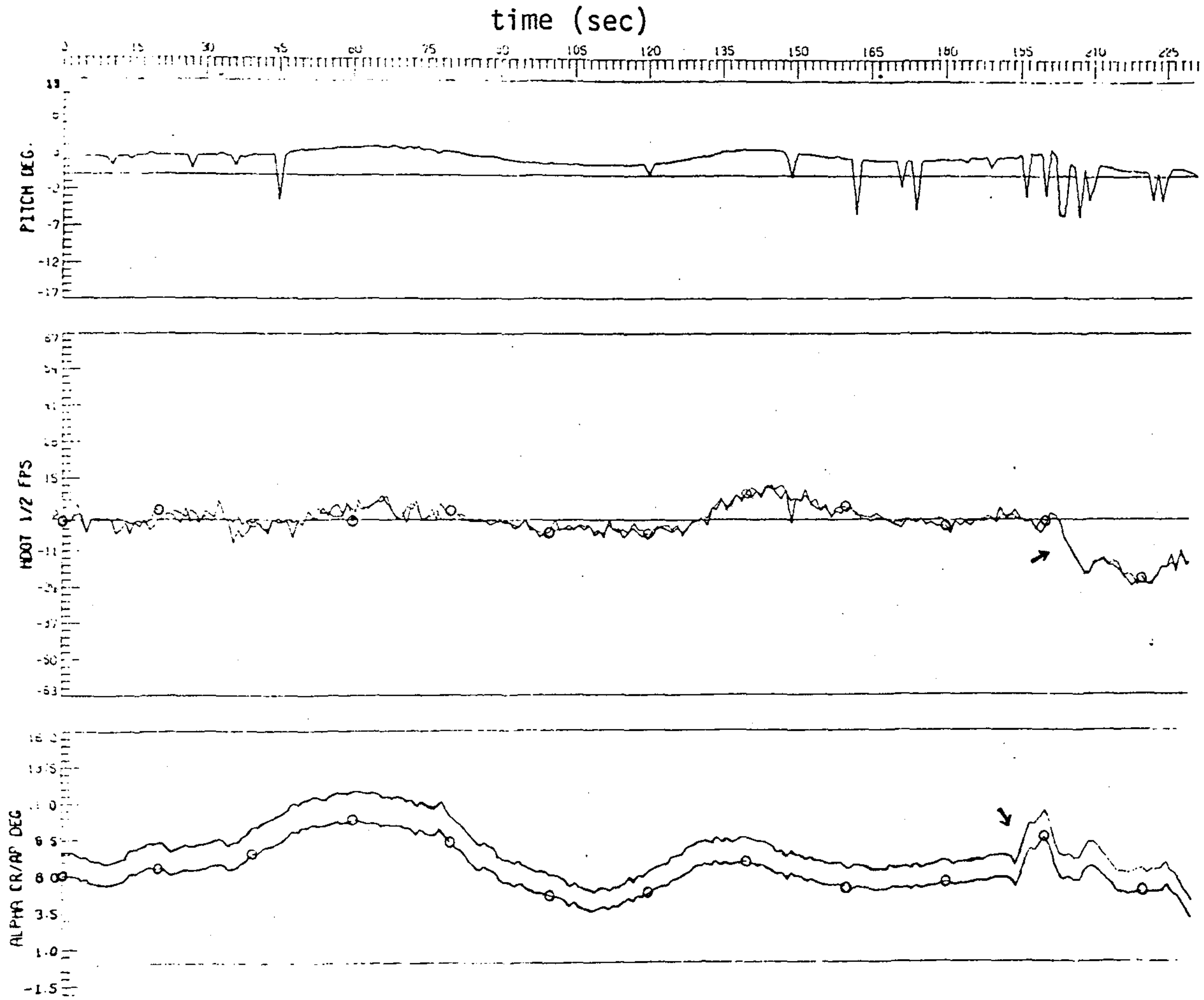


Figure 4.- TCV Flight S-183 wind rain shear study run 10A

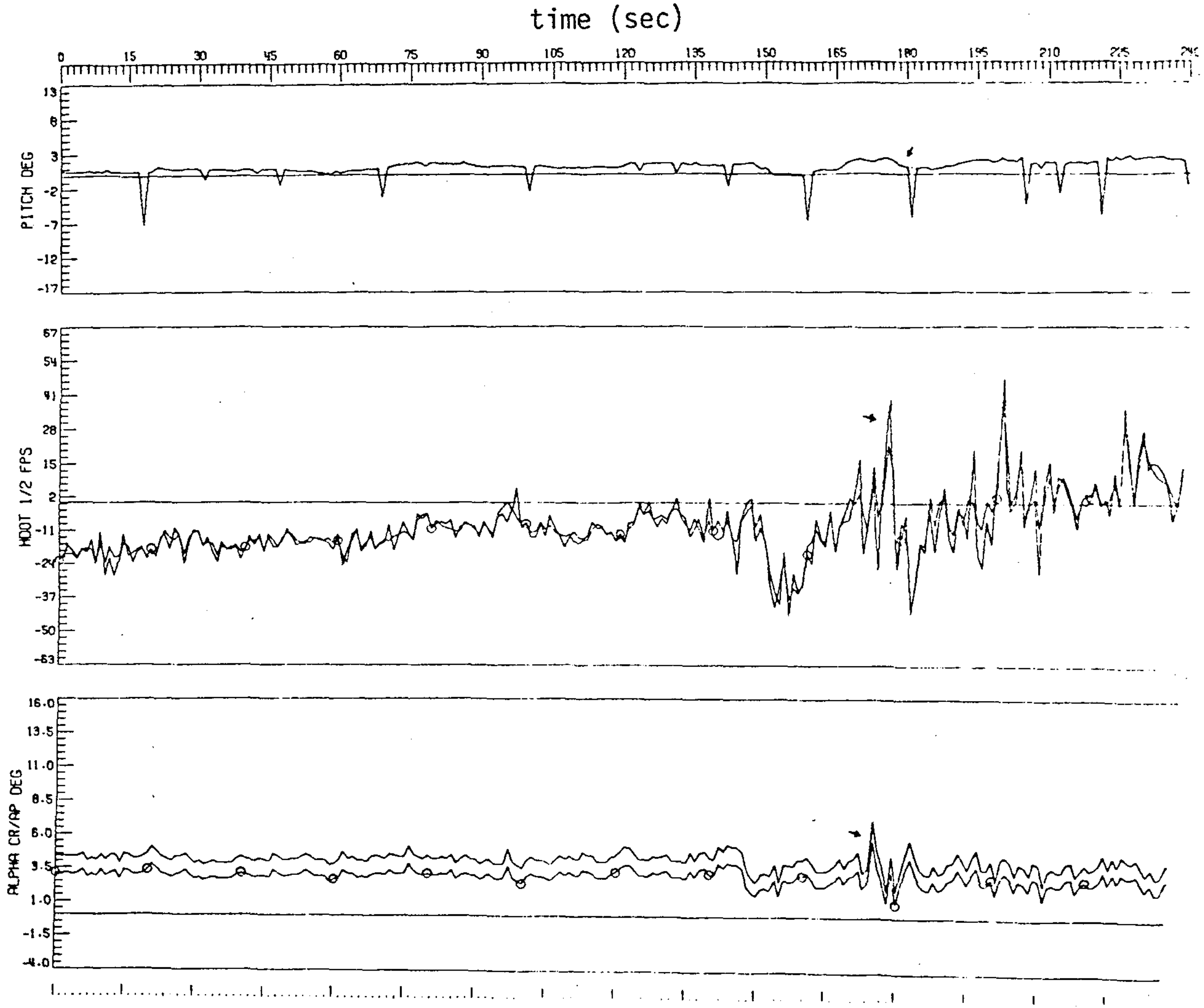


Figure 5.- TCV Flight S-183 wind rain shear study run 10C

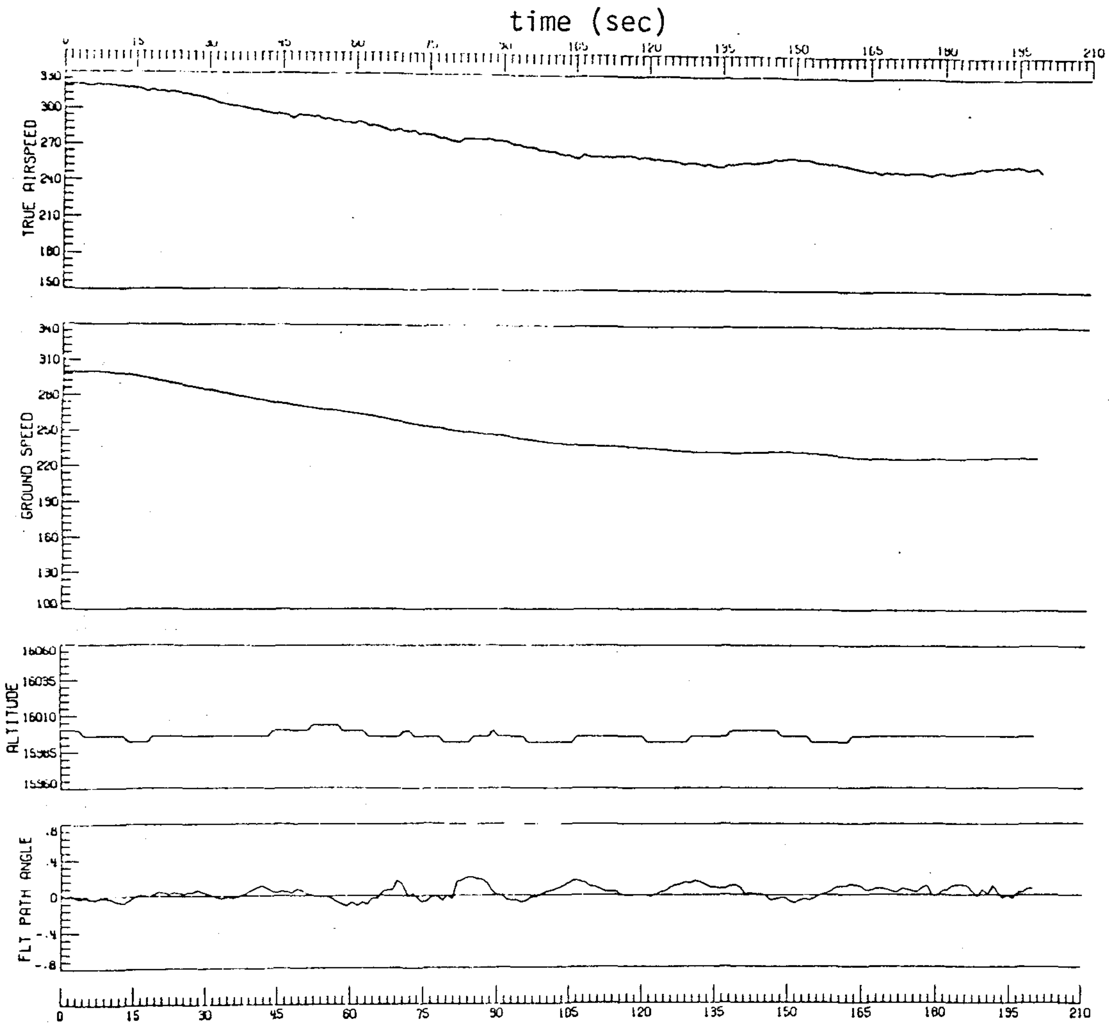


Figure 6.- TCV Flight 183 wind shear rain analysis

aerodynamic parameters which make the presence of severe meteorological factors such as heavy rain and downbursts seem unlikely. This data, together with the lack of confirmation of precipitation locations, precludes any conclusive proof or disclaimers of Luers' statements.

S-219A yielded about 25 minutes of flight data. Due to time limits and computer priorities, only the altitude and groundspeed from the navigation computers were analyzed. There were no sudden drops in altitude from loss of lift nor apparent decays in groundspeed from increase of drag. Nonetheless, the S-219A data reduction is far from complete. The other parameters should be obtained and reviewed before any conclusions can be drawn.

DISCUSSION

Despite the lack of evidence on the influence of heavy rain, the investigation procedure outlined in this report is believed to be valid. Following the guideline, horizontal (longitudinal) wind shears and vertical drafts were easily discernable in the flight data.

The major difficulty in the data reduction process was the uncertainty in when rain was encountered and how much rainfall occurred. Weather station reports only record total precipitation per hour, not the time and location of localized showers. The heavy rainfall analyzed by Luers had extreme rates of 200 mm/hr. and greater, which is not rare when short duration intervals are considered. To obtain conclusive evidence on Luers' theories, flight data in heavy rain must not only be available, but there should be means for correlating the flight data with actual weather conditions.

Another obstacle in any data evaluation is the isolation of heavy rain effects from the influences of the other aforementioned atmospheric factors. The suggested procedure to analyze this data is a process of elimination. The "signatures" of all other factors except rain should be examined at any sudden losses of altitude. A positive identification should dismiss that interval from further investigation. Only when the other "signatures" do not correspond to the flight data should rain-induced influences be considered.

These recommendations only apply to experimental flights such as those of the TCV B-737. A much more effective and informative exercise is a wind tunnel test with simulated rain. It is strongly urged that this be the first step before any actual flight tests are conducted in an extensive rain-effects investigation. Separate wind tunnel tests on the airfoil, the fuselage, and the total aircraft should be performed. The results would ease data analysis on the flight tests to follow. Comparison of results from these experiments can help redefine needs in the investigation.

CONCLUDING REMARKS

Conclusions drawn by James Luers from his study on heavy rain could have a major impact on flight safety. Debate has risen over his claim that "the magnitude of (the aerodynamic) penalties associated with heavy rain can be of the same order as that associated with wind shear."

From simulations, Luers' group has determined that the severity and effects of wind shears on several aircraft accidents/incidents have been very much overstated. Furthermore, Luers believes avoiding heavy rain cells during takeoff and landing approach can significantly lessen aircraft mishaps since it is the combined effects of wind shear and heavy rain which have been responsible for a number of accidents, while the severity of wind shear is actually about half of what it was previously cited to be.

Buried in the speculation of the roles heavy rain and wind shear play in aircraft performance deterioration is another possibility. Instead of being a direct contributor to the aerodynamic penalties, heavy rain intensifies other hazardous factors, specifically downdrafts. In a thunderstorm environment, falling precipitation drags the air downward, initiating a downdraft. Its evaporation cools the surrounding air, decreasing the air's buoyancy and intensifying the downdraft. Divergence of the downdraft at the surface produces a horizontal outflow which undermines and lifts the inflowing saturated warm air. As the moist air mass rises and cools, rain falls from this "tilted" updraft into the downdraft region. As more precipitation affects the downdraft air, the intensity of the vertical winds increases further, worsening flight conditions.

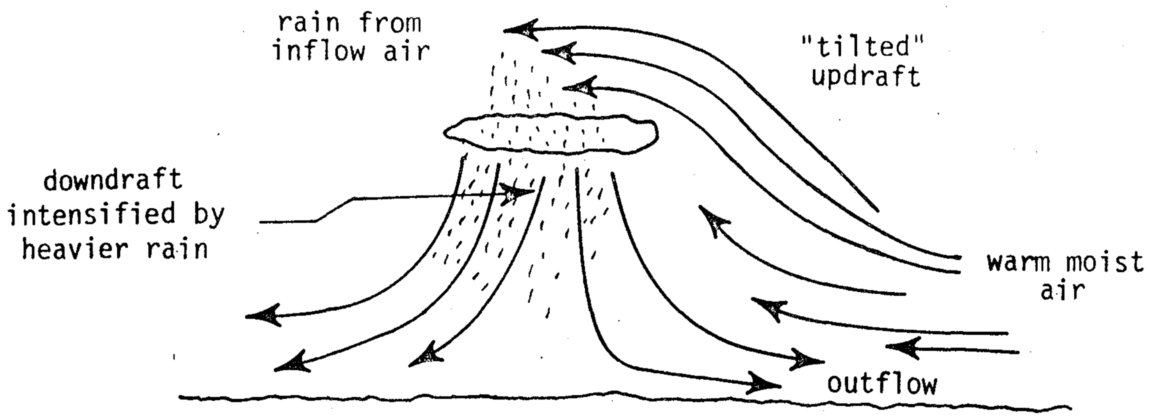


Figure 7.- Heavy rain influence on downdraft hazard

Jean T. Lee, meteorologist from the National Severe Storms Laboratory, has conducted extensive research and data collection on the hazards of severe storms. One significant aspect from his investigations is that it is not uncommon to find that the area of maximum precipitation in a thunderstorm does not coincide with the area of maximum gusts nor the area of greatest wind shear. In other words, flying away from the heaviest rain is no guarantee of a decrease in wind shears and other meteorological hazards. It is conceivable that the possibility of a mishap may be enhanced by flight through another part of the thunderstorm. The Luers study estimated an increase of drag of 5 to 20 percent on the aircraft deduced from analytical calculations on a roughened airfoil. Twenty percent drag rise is a very significant figure. But this is a contribution only to the skin friction drag. Induced drag predominates for an aircraft in the landing approach configuration (as were the accident cases examined by Luers). In terms of total drag, the maximum increment may only be about 5 percent due to the heavy rain.

Aerodynamic effects of heavy rain may or may not be as significant and dangerous as Luers reports, but until conclusive data is available, it is unwise to put wind shear and the prospective equipment of the detection and avoidance program in the back seat.

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16. Abstract

A guideline has been defined for the analysis of flight data to determine the effects of rain on the aerodynamic performance of an aircraft. It distinguishes and separates the effects of horizontal wind shears, downdrafts, gusts at the phugoid frequency, and rain based on various aerodynamic parameters. Flight data from NASA LaRC's TCV B-737 were inconclusive because precipitation rates encountered probably were not high enough. However, the guideline seemed to be valid and can be used on further flight data evaluations. Difficulties in this type of data anlaysis are discussed. Other indirect influences of rain on the degradation of airplane performance are also considered.

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