Analyses of Arrow Air DC-8-63 Accident of December 12, 1985: Gander, Newfoundland

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A performance analysis was conducted of the Arrow Air DC-8-63 takeoff accident at 10:15 GMT, December 12, 1985 at Gander, Newfoundland. A two-part study was conducted. A takeoff sensitivity analysis was performed using a digital, fixed stick simulation program to establish the relative performance degradation resulting from several factors that were candidate causes or contributing factors to the accident. The second approach was to reconstruct the accident trajectory by solving the airplane equations of motion using flight recorder data and known accident facts supplied by the Canadian Aviation Safety Board (CASB) as input. Consistent results were achieved from the two approaches.

Nomenclature

A = wing reference area
a_D = acceleration in the drag direction
a_L = acceleration in the lift direction
a_x = acceleration in the horizontal direction
a_z = acceleration in the vertical direction
C_D = drag coefficient
C_L = lift coefficient
C_m = pitching moment coefficient
$\bar{c}$ = mean aerodynamic chord
F_T = airplane thrust
g = gravitational acceleration
I_{yy} = moment of inertia about symmetry plane of the airplane
L_T = effective moment arm of the thrust vector
N = load factor
V = velocity relative to the Earth
$\dot{V}$ = time derivative of airplane velocity
V_a = true airspeed
V_z = climb rate
W = aircraft weight, mg
α = angle of attack
α' = $\theta - \gamma - \delta$
δ = angle between V_a and V
δ_T = angle between the thrust and the fuselage centerline
γ' = $\gamma + \delta$
ρ_a = air density
θ = pitch angle
$\ddot{\theta}$ = time derivative of pitching rate

Introduction

According to the Aviation Occurrence Report[1] issued by the Canadian Aviation Safety Board (CASB) Arrow Air Fight MF1285R, a Douglas DC-8-63 departed Cairo, Egypt, December 11, 1985 on an international charter flight to Fort Campbell, Kentucky via Cologne, Germany and Gander, Newfoundland. Onboard were eight crew members and 248 passengers. The flight had been chartered by the Multinational Force and Observers (MFO) to transport troops, their personal effects, and some military equipment to and from peacekeeping duties in the Sinai Desert. All 248 passengers who departed Cairo on December 11, 1985 were members of the 101st Airborne Division (United States Army), based in Fort Campbell.

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The flight arrived at Gander at 9:04 am. Passengers were deplaned, and the aircraft was refueled. The flight engineer was observed conducting an external inspection of portions of the aircraft. The passengers then reboarded. Following engine startup, the aircraft was taxied to runway 22 for departure. Takeoff on runway 22 was begun from the intersection of runway 13 at 10:15 am. The aircraft was observed to proceed down the runway and rotate in the vicinity of taxiway "A." Witnesses to the takeoff reported that the aircraft gained little altitude after rotation and began to descend. Several witnesses, who were traveling on the Trans-Canada Highway approximately 900 ft beyond the departure end of runway 22 testified that the aircraft crossed the highway, which is at a lower elevation than the runway, at a very low altitude and in a right bank. The pitch angle was seen to increase, but the aircraft continued to descend until it struck downsloping terrain approximately 3000 ft beyond the departure end of the runway. The aircraft was destroyed by impact forces and a severe fuel-fed fire. All 256 occupants onboard sustained fatal injuries.

Analysis of this accident by the CASB determined that the airplane impacted into a wooded area 2975 ft from the end of the runway and 720 ft to the right of the extended centerline. The impact altitude was 147 ft below the elevation of the departure end of the runway. A survey and analysis of the damage path through the trees indicated that at impact the aircraft was at a 9-deg pitch-up, right-wing down attitude and 12-deg descent angle. This corresponds to a 21-deg angle of attack—well beyond the stall angle of the airplane. The elevator deflection at impact was ≥ -24 deg, indicating full nose-up deflection. The failure of the aircraft to be detected by the Mode C radar readout indicated it achieved a maximum altitude of less than 125 ft.

The aircraft was equipped with a Sundstrand cockpit voice recorder (CVR) and a United Control flight data recorder (FDR). The cockpit voice recorder was not functioning properly and did not provide the cockpit conversation that occurred during the takeoff. The four-channel FDR provided traces of airspeed, pressure altitude, heading, and vertical acceleration as shown in Fig. 1. Although the vertical acceleration recordings on the FDR foil were substandard, usable data were obtained from each channel. Visual inspection of Fig. 1 provides several likely conjectures about the takeoff event. From the load factor (vertical acceleration) and pressure altitude traces, liftoff probably occurred in the time range of 1:25–1:28 (min:s). Stall likely occurred near 1:33 where the load factor indicates a sharp downward acceleration and the heading begins deviating from 220 deg (indicative of a stalled wing). The airspeed at this time was approximately 165 kt, well above the 144-kt clean wing stall speed of the airplane.

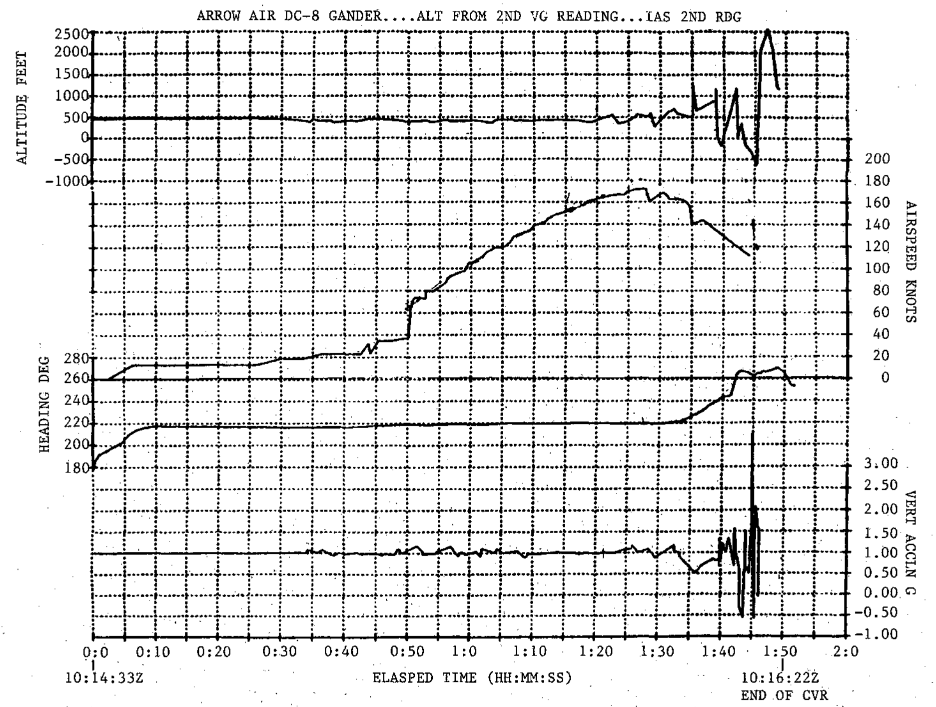

Fig. 1 Flight data recorder information.

Other indications that the airplane actually stalled are the erratic pressure altitude and airspeed profiles after about 1:30. An analysis of the accident by the CASB uncovered the following irregularities that may have caused or been contributing factors to the accident.

Reduced Engine Thrust/Loss of Engine

Engines 1, 2, and 3 were determined to be operating at high-power settings at ground impact. Engine 4 was determined to be operating at a lower rpm than the other three engines when it struck the ground. It could not be conclusively determined how much lower the impact rpm was, although the position of the bleed valve strongly suggests that, prior to impact with the ground, the engine rpm fell below 53%. It could not be determined if this lower ground impact rpm was the result of the ingestion of debris as the engine passed through trees immediately prior to ground impact or if the lower rpm was a condition that occurred prior to descent into the trees. Exhaust gas temperature (EGT) indications for engine 4 were approximately 40 deg hotter than the other three engines. As a result, the Cologne/Cairo sector crew was retarding the throttle slightly on takeoff to keep the temperature under limiting values. It is reasonable to assume that the accident crew was doing the same. Information supplied by the engine manufacturer demonstrated that such an action would reduce total engine thrust by about 2.5%.

Thrust Reversers Deployed

Consideration was given to the possibility that a reverser had deployed in flight and, as a result of crew actions, had been stowed prior to impact. Initial examination of the number 4 thrust reverser at the accident site raised this possibility. When found, the translating ring of the reverser system had been turned inside out, giving the appearance that the reverser had been open at ground impact. This possibility was further supported by the aircraft's slight turn to the right shortly after liftoff. As a result, all four engine thrust reversers were subjected to close scrutiny by investigators. In the case of engines 1, 3, and 4, the translating rings were determined to be in the forward position and the deflector doors faired. In the case of engine 2, the translating ring may have been aft of the forward stop but was at least some 16 in. forward of the rear stop, and the deflector doors were faired.

Early Rotation of Airplane

There was considerable evidence to suggest that the crew-calculated takeoff weight (330,625 lb) at Gander was less than the actual takeoff weight. The CASB estimated that the actual takeoff weight exceeded that calculated by the crew by about 14,000 lb. The most significant contributing factor to this underestimation was the use of an average passenger weight that was significantly less than the actual weight of a U.S. Army soldier with web gear, weapon, and the quantity of other carry-on baggage described by witnesses. This underestimation of weight would have resulted in the use of takeoff reference speeds below those appropriate for the actual takeoff weight. The takeoff reference speeds for the crew-calculated weight are between 3 and 5 kt lower than the reference speeds for the CASB estimate of the actual weight, that is, 344,500 lb. Other evidence suggests that the crew may have inadvertently used takeoff reference speeds for a takeoff weight about 35,000 lb below the actual takeoff weight. Examination of the wreckage suggested that the reference bugs on the co-pilot's airspeed indicator may have been set at the reference speeds appropriate for a takeoff weight of 310,000 lb.

Ice on Wings

Weather conditions at Gander were conducive to ice accretion on the wings of the airplane during its approach to Gander for its 9:04 am arrival as well as while sitting on the ground prior to its takeoff attempt at 10:15 am. The weather observer reported very light freezing drizzle and light snow grains at his 9:00 am observation. The 9:30 am observation also consisted of freezing drizzle mixed with snow grains. By 9:45 am a special report was issued for only light snow grains. Moderate in-cloud aircraft icing between 700 ft and 4000 ft was also reported by several aircraft operating to or from Gander near the time of the accident.

Previous research and flight tests have demonstrated that small amounts of ice on the leading edge of a wing can significantly degrade the airplane performance and flight characteristics.[2] The performance degradation results in decreased lift and increased drag. Of special significance is the decrease in stall angle (increase in stall speed) caused by the surface roughness associated with ice on the leading edge of the wing. Several previous accidents involving similar type aircraft have been related to ice contamination on the leading edge.[3,4]

Analysis

The University of Dayton Research Institute (UDRI) was contracted by the Canadian Aviation Safety Board to analyze the Gander DC-8 accident by using techniques previously developed in the reconstruction of the Pan Am New Orleans accident of 1982.[5] Specifically, the UDRI was directed toward assessing the influences of the various potential causes of the accident and to determine their consistency in explaining the accident relative to the known factual information. A two-part study was conducted. A takeoff simulation analysis was performed using a digital, fixed stick simulation program to establish the relative performance degradation from the factors considered as potential causes of the accident. The second approach was to reconstruct the accident trajectory by solving the airplane equations of motion using the FDR data and known facts about the accident as primary input. The following sections describe the analysis performed.

Part 1: Takeoff Sensitivity Analysis

A two-dimensional, three degree-of-freedom digital takeoff program was used to simulate various takeoff scenarios. A normal takeoff trajectory was simulated and then various abnormal trajectories were generated under assumed conditions that might have produced performance degradation. The airplane equations of motion used in the simulation, as described in Luers and Reeves,[6] are

$$\dot{V} = -g\sin\gamma' + \frac{F_T}{m}\cos(\delta_T + \alpha') - (C_D \cos\delta - C_L \sin\delta)\left(\frac{A\rho_a V_a^2}{2m}\right) \tag{1}$$

$$\dot{\gamma}' = -\frac{g}{V}\cos\gamma' + \frac{F_T}{mV}\sin(\delta_T + \dot{\alpha}') - (C_D \sin\delta - C_L \cos\delta)\left(\frac{A\rho_a V_a^2}{2mV}\right) \tag{2}$$

$$\ddot{\theta} = \frac{F_T L_T}{I_{yy}} + \frac{C_m\bar{c}}{I_{yy}}\left(\frac{A\rho_a V_a^2}{2}\right) \tag{3}$$

The aerodynamic and thrust data were provided to the CASB by the Douglas Aircraft Company for the DC-8-63 airplane. The takeoff weight was considered to be 344,500 lb. The corresponding "V" speeds are $V_R = 154$ kt and $V_2 = 166$ kt. For the sensitivity analysis, a normal takeoff consisted of initiating rotation 1 s after V_2, rotating to a pitch of approximately 13 deg at a rate < two deg/s and climbing out at $V_2 +$ 10 kt. This was achieved in the simulator program by deflecting the elevator linearly to -14 deg over a 6-s period beginning 1 s after V_R then backing the elevator to -13 deg over the next 2 s. This resulted in the aircraft rotating to a pitch of 12.6 deg at a rotation rate slightly less than 2 deg/s and reaching $V_2 + 10$ at 35 ft and climbing out at a stabilized speed of $V_2 = 10$ (see Figs. 2 and 3).

The potential accident contributing events that were evaluated with the sensitivity analysis were: 1) early rotation of airplane, 2) reduced engine thrust, 3) loss of an engine, 4) one engine in thrust reversal mode (simulated as loss of two engines), 5) ice on wings, 6) combinations of the above. The individual effect of each factor on a normal takeoff as well as the combined effects of several factors were determined. The details and results from each simulation are as follows.

Early Rotation

Since the V_R and V_2 speed bugs on the co-pilots instrument panel, as observed from the wreckage, corresponded to the aircraft being at a lighter weight than that deduced after the accident, the result of premature rotation at the corresponding V_R speed was simulated. The input conditions were 1) begin rotation at the instant $V_R = 146$ kt + 1 s, 2) deflect elevator to -14 deg over 6 s, and 3) backoff elevator to -13 deg over 2 s. The results are shown in Figs. 4 and 5. The climb rate changes very little from a normal takeoff. Airspeed can be maintained. The angle of attack is about one degree higher than for a normal takeoff. A very adequate stall margin still exists. This scenario does *not* produce serious performance degradation.

Reduced Engine Thrust

Because one engine was known to be running hot, there are indications that the engine may have been throttled back during takeoff. The effect of a 1500-lb loss in thrust in one engine was simulated. Other input was the same as for a normal takeoff. The results show only a slight reduction in climb rate. Airspeed is maintained. The angle of attack is almost unchanged from a normal takeoff. There is no significant degradation in takeoff performance.

Loss of One Engine

In the postcrash analysis, one engine exhibited less rotational damage than the other three. The effects of an engine loss at V_R and at V_R + 5 s were simulated by decreasing the

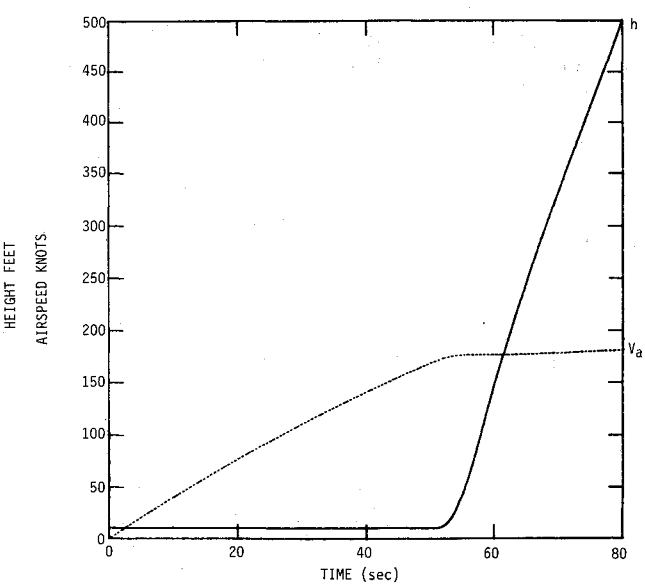

Fig. 2 Normal takeoff.

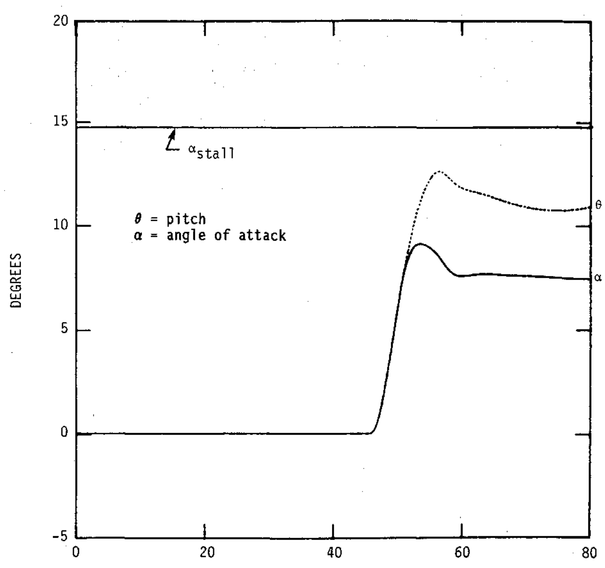

Fig. 3 Normal takeoff.

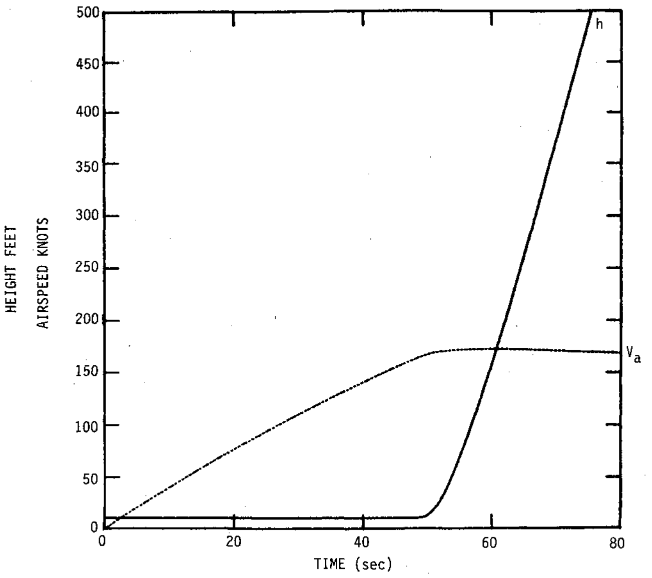

Fig. 4 Early rotation.

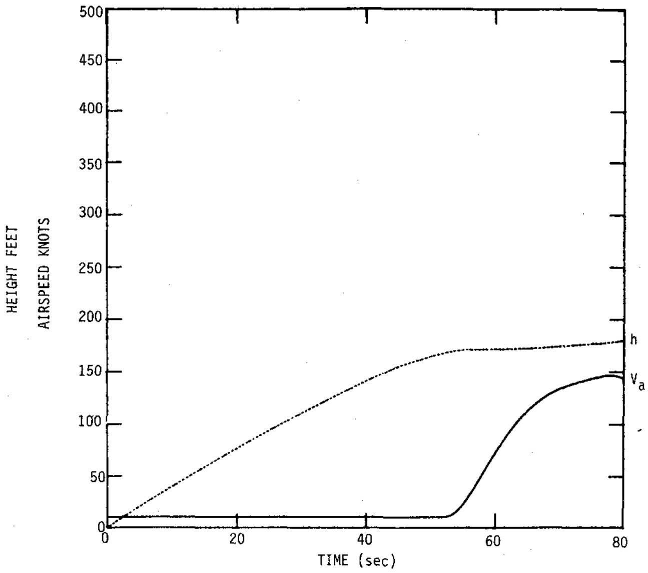

Fig. 6 Engine loss at V_R.

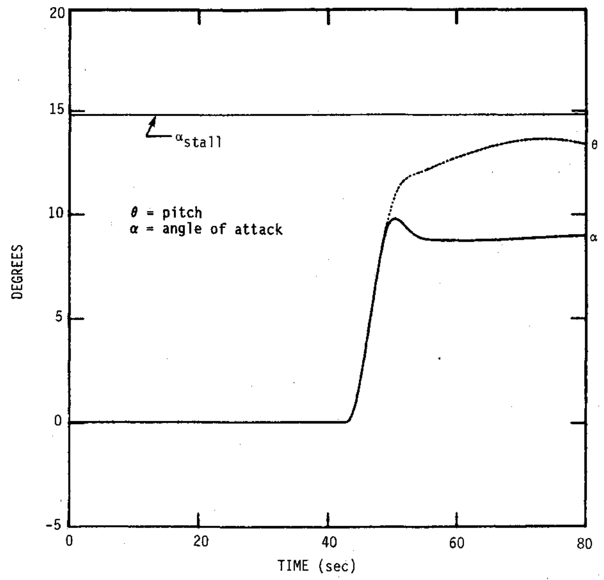

Fig. 5 Early rotation.

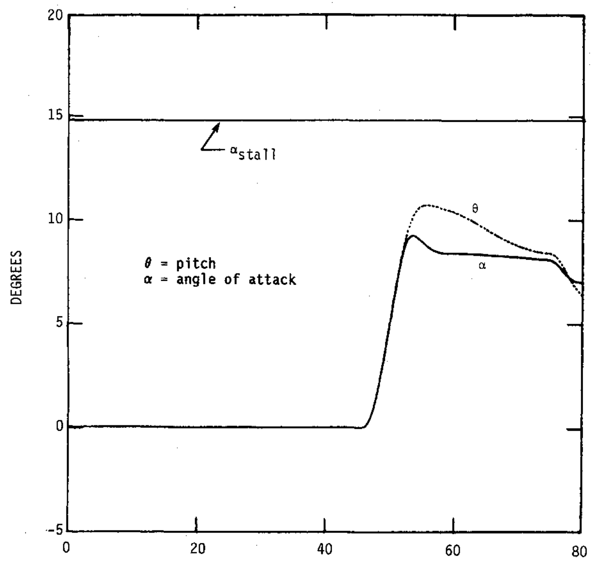

Fig. 7 Engine loss at V_R.

total thrust of the four-engine airplane by 25%. Other inputs were the same as for a normal takeoff.

The results are shown in Figs. 6 and 7 for engine loss at V_R. The climb rate is near normal to 100–150 ft, at which time it drops sharply to near zero. However, the airspeed is maintained and even increases slightly. Altitude is also maintained. The angle of attack is about one degree higher than normal with no danger of stall. The results for engine loss at V_R+5 s are similar to those for engine loss at V_R with slightly less performance degradation. These results confirm the expected normal performance deterioration resulting from the loss of an engine. This is not a likely cause of the DC-8 Gander accident in which an airplane stall is apparent.

Engine in Thrust Reversal Mode

To assess worst case possibilities consisting of the use of one engine in a thrust reversal mode, a simulation was made by assuming a loss of thrust from two engines at $V_R + 5$ s. The results are shown in Figs. 8 and 9.

The airplane climbs initially then begins to lose altitude, then increases speed, and again starts to climb. It is able to maintain airspeed at a low altitude. The angle of attack is very similar to that of a normal takeoff. This scenario will not result in a stall unless the airplane is allowed to climb rapidly at takeoff until sufficient airspeed is lost to stall the airplane at an altitude well above the ground level. Since, in the Gander accident, the aircraft barely climbed off the ground, the two-engine loss (one engine in thrust reversal) scenario is not a likely event that caused the accident.

Ice on Wings

Weather conditions observed at Gander suggest the possibility that the aircraft penetrated supercooled water droplets or light freezing rain while landing at Gander approximately 1 hr and 10 min prior to takeoff. Ice on wings, due to roughness, is known to cause serious loss in lift near $C_{L\max}$ and a significant rise in drag. To simulate this effect, the DC-8-63 lift and drag curves were modified. The modified curves represent only the generic nature of what can be expected with an ice-roughened airfoil. The curves should not be considered to represent how the DC-8-63 actually performs when exposed to a specified amount of icing. Fig. 10 shows the basic C_D and C_L curves for the DC-8 aircraft and aerodynamically roughened curves derived from Haines and Luers[7] based on an equivalent sandgrain roughness of $K_s = 1.4$ mm. The results of simulations using the rough surface curves are shown in Figs. 11 and 12.

The airplane climbs with a pitch of about 11 deg while maintaining airspeed but is dangerously close to the rough wing stall angle of attack. In fact, during rotation, the stall angle is actually reached. If the airplane were rotated to a 12- or 13-deg pitch attitude (as would be expected), the airplane would stall at the end of the rotation at a very low altitude with recovery impossible. This scenario provides a reasonable explanation of the accident.

Combinations of Possible Causes

Simulations were also made of takeoffs assuming a combination of two or more of the possible accident causes. The combinations considered were 1) loss of one engine and early rotation, 2) ice on wings and early rotation, and 3) ice on the wings, loss of one engine, and early rotation. From these simulations, only the latter two that include aerodynamic penalties resulting from ice on the wings provide a scenario that is consistent with the DC-8 accident, i.e., the airplane stalled at a low altitude.

Part 2: Accident Reconstruction

General Description

The Arrow Air Gander accident was reconstructed using the technique developed by UDRI for the analysis of the Pan Am New Orleans take-off accident[5] in which a rain roughened airfoil was suspected. In this accident reconstruction, the equations of motion are integrated in an inertial frame of reference. All of the forces acting on the airplane are divided into their vertical and horizontal components and are related proportionally to the vertical and horizontal accelerations. The vertical and horizontal velocities are derived by integrating the accelerations. The aircraft position is derived by integration of the velocity. The aircraft position vs time can be compared with the ground impact position of the airplane for consistency.

The vertical and horizontal accelerations in the aircraft's ground path frame of reference are

$$a_z = a_D \sin\gamma + a_L \cos\gamma \tag{4}$$

$$a_x = a_D \cos\gamma + a_L \sin\gamma \tag{5}$$

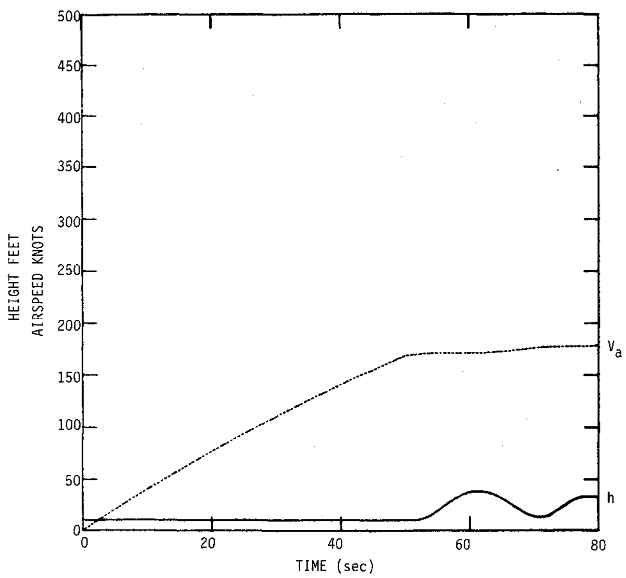

Fig. 8 Loss of two engines.

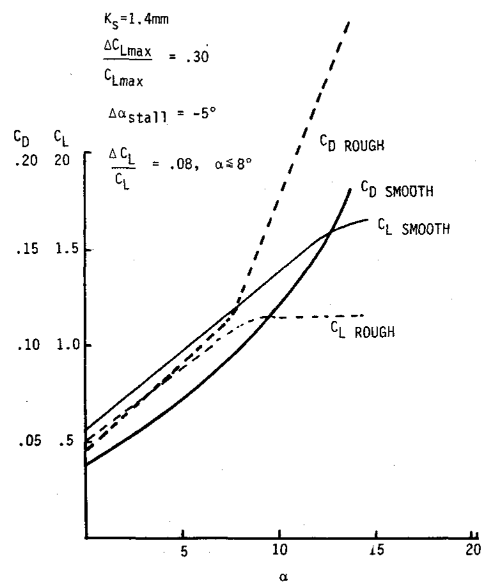

Fig. 10 Lift and drag curves for airplane with roughened wing surface.

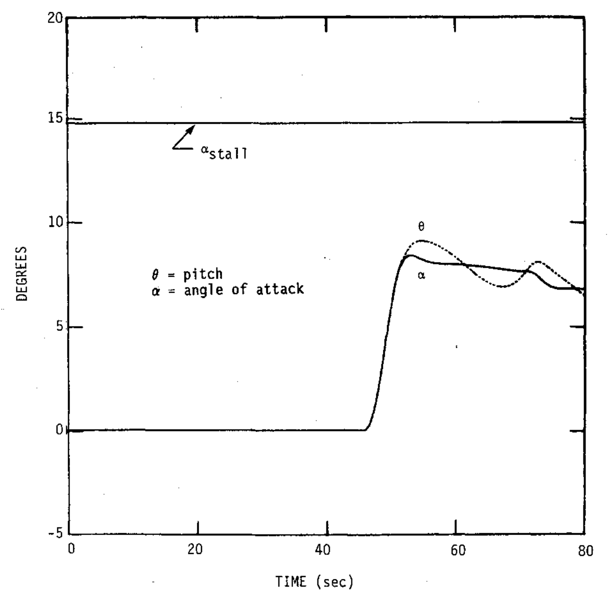

Fig. 9 Loss of two engines.

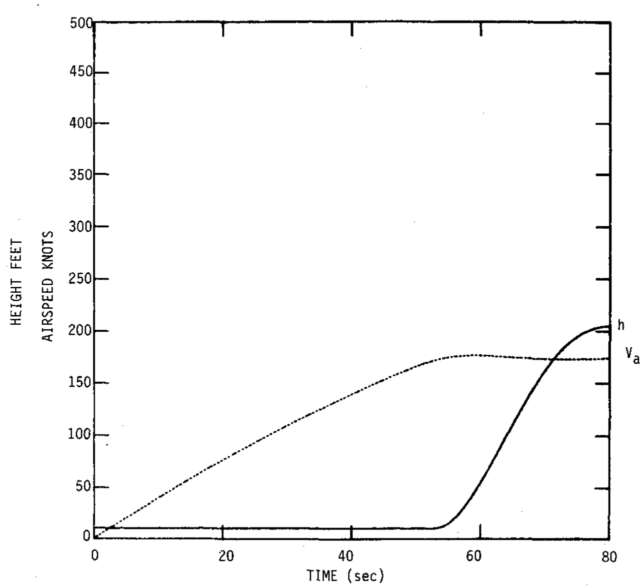

Fig. 11 Ice on wings.

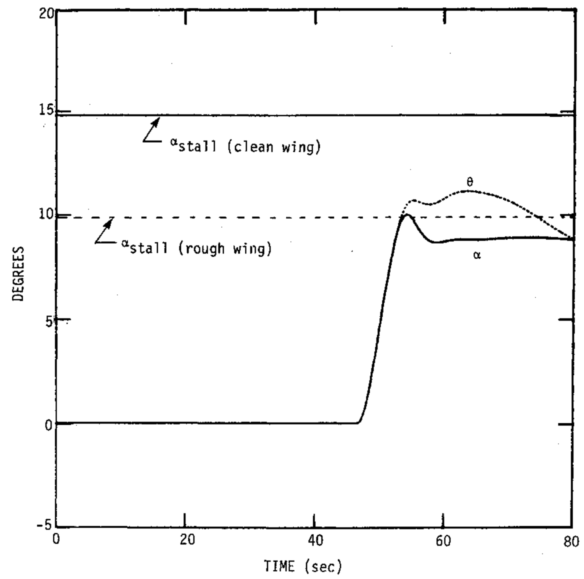

Fig. 12 Ice on wings.

The climb angle γ is given by

$$\gamma = \sin^{-1}(V_z/V_a) \tag{6}$$

where the vertical wind is assumed to be zero. The drag and lift equations are:

$$a_D = (F_T/m)\cos(\delta_T+\alpha) - (C_D/m)(\rho_a A/2)V_a^2 - g\sin\gamma \tag{7}$$

$$a_L = (F_T/m)\sin(\delta_T+\alpha) + (C_L/m)(\rho_a A/2)V_a^2 - g\cos\gamma \tag{8}$$

Equations (4-8) can be shown to be equivalent to Eqs. (1) and (2). The values for mass m, thrust F_T, offset angle δ_T, and wing reference area A for the DC-8 aircraft were provided by the manufacturer to the CASB and made available to UDRI for this study. The meteorological data provided the air density ρ_a and the assumed constant wind speed. The clean wing drag C_D and lift C_L curves were also provided by Douglas Aircraft Company to the CASB for the appropriate takeoff configuration as a function of angle of attack. The true airspeed was derived from the FDR trace of indicated airspeed taking into account the angle of attack. The FDR trace of the vertical acceleration (load factor) was related to the horizontal and vertical accelerations through the pitch angle as

$$(N-\cos\theta)g = a_L\cos\alpha - a_D\sin\alpha \tag{9}$$

where N is the load factor and the pitch angle θ is

$$\theta = \alpha + \gamma \tag{10}$$

The numerical solution of Eqs. (4-10) using the available input data is sufficient to define the aircraft trajectory, the pitch history, and all other variables. However, if performance deterioration due to ice on the wings is assumed then the lift and drag coefficients become unknowns and some additional constraints on the horizontal acceleration and pitch time history are needed to obtain a unique solution. A multinested iteration scheme is then required for solving Eqs. (4-10). The inner iterations involve a unique solution for each time step, and the outer iterations involve resetting the initial conditions for the equations of motion in order to be consistent with the known facts about the impact. Dietenberger et al.[5] give a detailed account of the solution processes.

For analyzing the Gander accident, an additional moment equation, i.e., Eq. (3) was used to calculate the elevator deflection. This required development of an algorithm to derive the pitch rate and rotational acceleration. The actual terrain elevation was included in the airborne segment of run and used to calculate the ground effects on lift and drag. During different segments of the trajectory, the equations of motion were solved for different variables depending on assumed and known conditions. The method of solution was as follows:

1) During the ground takeoff run to FDR time = 1:20, the airplane pitch is set parallel to the runway, and the lift equation is used in calculating the rolling friction. The aircraft runway acceleration is obtained from the drag equation with the rolling friction included. No drag or lift penalties are assumed during this time period. Alternately the ground acceleration could have been derived from the derivative of the FDR airspeed trace. However, this is unreliable at low air speeds.

2) When the airspeed reached 70 kt, its accuracy became acceptable, and the aircraft runway acceleration a_D is derived from the derivative of the true airspeed. This is valid only for a constant windspeed and for the airplane pitch remaining parallel to the runway. The drag equation with the included rolling friction is used to solve for the drag coefficient. A significant increase of drag over the baseline drag implies airplane surface contamination or loss of engine power (on the runway) or both.

3) Just before the beginning of rotation at time t = 1:20 and until liftoff, the airplane acceleration is derived from the derivative of the airspeed so that the drag equation is solved for the drag coefficient as the angle of attack increases. A pitch time history is assumed during rotation to account for the lift coefficient influence on the rolling friction.

4) At liftoff and thereafter, the load factor data along with a reasonable pitch history and horizontal acceleration profile, are used to determine the aircraft's vertical acceleration. Smoothed values of load factor derived from Fig. 1 were used as input to the equations. This allowed solving the equations of motion for the lift C_L, drag C_D, and elevator deflection as a function of FDR time.

The boundary conditions and constraints that had to be satisfied in solving the equations of motion were:

1) Airplane tail strikes a tree at a position of x = 2881 ft from the end of the runway, y = −720 ft right of the extended runway centerline, and z = 278 ft above sea level.

2) At initial impact the pitch angle = 10 deg, the descent angle = −12 deg, and the yaw angle = −9 deg. (Although the CASB Report 85H50902 indicates a pitch angle of 9 deg at impact, the UDRI was given 10 deg as the initial estimate of the pitch attitude by the CASB. A 1-deg difference in pitch has negligible influence on the analysis and conclusions.)

3) Constant wind of 4 kt at 290-deg heading.

4) Liftoff (wheels off the runway) at a pitch angle of 8-8.5 deg and before the airplane reaches the end of the runway.

5) Airplane altitude less than 125 ft above runway throughout flight.

6) Elevator deflection at tree impact ≈ −24 deg.

In solving the equations iteratively, certain parameters were found to have primary influence on satisfying specific constraints. In particular, 1) brake release time was constrained iteratively to give an average −1.24 kt headwind during the takeoff run, 2) brake release position was constrained iteratively to give the correct impact x position at impact time t = 1:39, 3) liftoff time was constrained iteratively to give the correct impact z position at impact time, 4) yawing effect due to asymmetric wing stalling was constrained iteratively to give impact y position at impact time, 5) a constant value for a_D during the airborne segment was iteratively derived to obtain a nearly constant headwind and also provide consistent drag vs lift penalties, and 6) a pitch history was assumed to provide a reasonable pilot response (8 deg at liftoff and 10 deg at tree impact), consistent lift and drag penalties, and a less than normal rotation rate due to the lift and drag penalties.

Results

The solution of the equations of motion of the aircraft can be shown to determine the lift coefficient to a high level of accuracy. The derived lift coefficient is largely insensitive to the assumptions that had to be made including an assumed pitch time history. The resulting lift coefficients that were calculated do not approach what is expected for a clean aircraft passing through $C_{L\max}$ and terminating at impact with a stall angle of attack of 21 deg. The drag coefficients derived from solving the equations of motion are not as accurate as the lift coefficient because it is dependent on the assumed thrust. Loss of thrust from one engine, for example, cannot be distinguished from a drag coefficient increase of ≈ 0.05. Our investigations of possible scenarios, including those in the part 1 analysis, show that acceptable solutions to the aircraft equations of motions using the FDR data as input, subject to the known boundary constraints must at least include a loss of lift and a severe drag increase. Ice on the airplane is an apparent cause of these aerodynamic penalties. The two probable solution trajectories are described as follows.

Scenario 1: Aerodynamic Penalties Due to Ice on Airplane

Figure 13 shows the FDR pressure altitude trace (too erratic to be of use in the analysis) and the derived aircraft trajectory vs ground elevation. The airplane barely climbed near the end of the runway and then started to descend rapidly. Its center of gravity altitude was about 140 ft below the runway when the tail struck the tree.

Figure 14 provides results about elevator deflection and angle of attack for three different assumed pitch time histories. Each pitch profile assumes the nose began to rise at about time 1:19, shortly after V_R at a rate of 1 deg/s. At 1:27 the airplane wheels lifted off the ground, which required a pitch angle of 8 deg. The pitch was assumed to continue to increase to 14, 12.5, and 10 deg, respectively, at a rate of 1 deg/s. Pitching to a limit of 14 deg gave the most consistency between lift and drag penalties that are representative of ice accretion on an airplane. Other pitch history assumptions, i.e., the 12.5- or 10-deg pitch limits had only a minor effect on changing the aircraft trajectory. The derived elevator deflection time history indicates that after the end of rotation, it decreased monotonically (more negative), even while the nose was lowering to a 10-deg pitch. The derived elevator deflection of -23.3 deg at time 1:39 and the derived angle of attack of 22 deg are consistent with known impact conditions. No scenario utilizing clean wing aerodynamics could be found that pro-

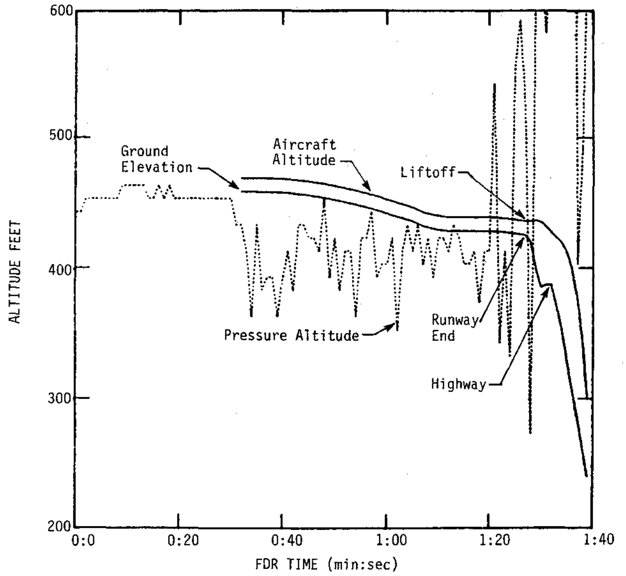

Fig. 13 Plot of pressure altitude, ground elevation, and aircraft center of gravity in ft above sea level (ASL) vs FDR time for scenario 1.

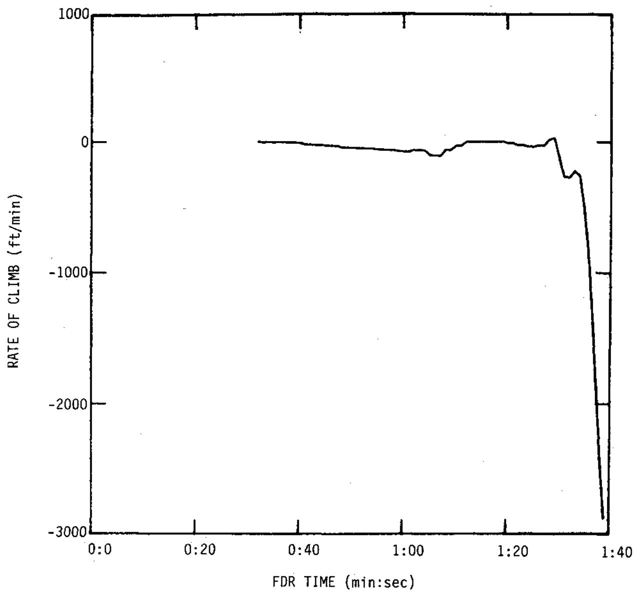

Fig. 15 Plot of rate of climb vs FDR time for scenario 1.

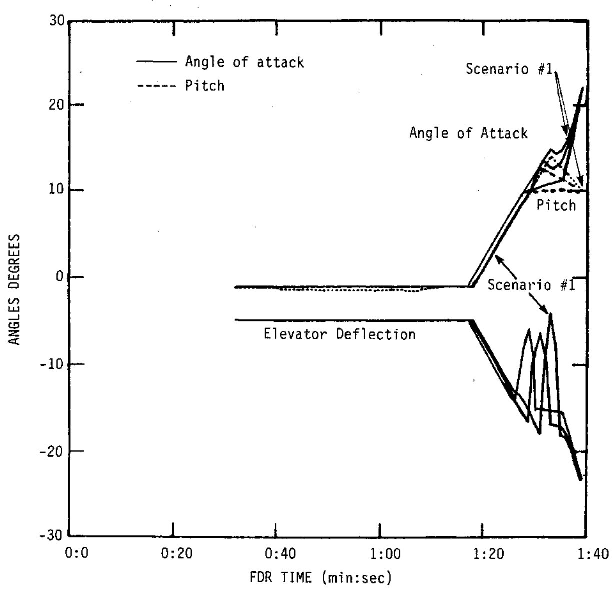

Fig. 14 Plots of assumed pitch history and the derived angle of attack and elevation deflection history for scenario 1; two other assumed pitch histories are included for comparison.

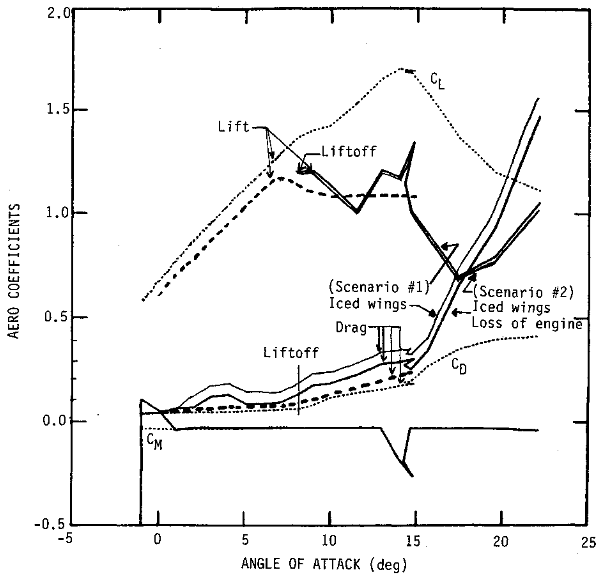

Fig. 16 Aerodynamic data relating to each scenario.

vides agreement with the angle of attack and the elevator deflection at impact.

Figure 15 shows the climb rate throughout the trajectory. A positive climb only occurred for a few seconds after liftoff. At impact the descent rate approached 3000 ft/min.

In Fig. 16 the dotted lines represent clean wing C_L, C_D, and C_M obtained from the aerodynamic data for the DC-8 aircraft. The solid lines represent C_L, C_D, and C_M derived from the method of solution discussed earlier for the case of pitching up to 14 deg. At angles of attack less than 15 deg (during the airborne segment of the flight) a 20–30% loss in the lift coefficient is noted, and at angles of attack greater than 15 deg the loss in the lift coefficient is 30–50%. At angles of attack less than 9 deg, the drag increment is about 200% of clean wing drag, and at angles of attack greater than 10 deg, the drag increment decreased to 100% of clean wing drag. At impact, the angle of attack was 22 deg, the drag increment was more than 200%, and $C_D = 1.5$. This value seems extremely high even for a deep stall. A re-examination of Fig. 1 shows a questionable steep drop in airspeed during the last 3 s before impact that gives rise to such an unreasonably high drag coefficient at initial impact.

Scenario 2: Aerodynamic Penalties Due to Wing Ice and One Engine Loss

In this solution, for the equations of motion, a loss of thrust from one engine is assumed to have occurred at time 1:20. This scenario also produced an acceptable solution to the equations of motion. The results shown in Figs. 13–16 from scenario 1 are practically identical to the results obtained for scenario 2 with the only difference being the derived values of drag coefficient. As shown in Fig. 16, instead of the 200% increment in C_D for angles of attack less than 9 deg found in scenario 1, we have about a 100% increment in drag for scenario 2. Thus, loss of an engine is equivalent to a drag coefficient increment of about 0.05. The lower increment in drag coefficient for the scenario 2 solution is more representative of that expected for a roughened airfoil.

Conclusions

The sensitivity analysis provided conclusions totally compatible with the accident reconstruction. The two accident scenarios are: 1) wing icing and 2) wing icing and loss of engine. The major factor in question is whether in addition to wing ice, an engine failure occurred during rotation. Fig. 16 reviews the aerodynamic data germane to the analysis. Note that the derived lift curve is essentially the same for both scenarios and agrees well with the assumed lift curve for a roughened airfoil that was used in the sensitivity analysis. The drag curve derived from scenario 1 (iced wings only) is considerably higher than that for scenario 2, which includes engine loss. The iced wing/engine loss drag coefficient curve better agrees with the generic drag coefficient for the roughened airfoil used in the sensitivity analysis but still exceeds the roughened airfoil curves. Some of this unexpected drag increase may have resulted from increased friction drag due to ice on the fuselage and other parts of the airplane. The drag coefficient derived from the iced-wing only scenario appears considerably larger than is normally expected for a roughened wing. This is especially true at low angles of attack before liftoff where a nearly 200% increase in derived airplane drag coefficient resulting from ice on the wings and fuselage far exceeds the expected performance degradation.

The conclusions are summarized as follows:

1) Any satisfactory explanation of the Arrow Air DC-8-63 (stall) accident requires significant loss of lift and increase in drag coefficient consistent with ice accretion on the wings of the airplane.

2) Ice accretion coupled with the loss of thrust from one engine during rotation also provides a satisfactory explanation of the accident. This explanation derives a drag penalty more consistent with that expected for an ice roughened airfoil. Inaccuracies in FDR data and the assumptions required to solve the equations of motion however prevent a positive determination of whether or not an engine loss occurred. Supporting evidence from postcrash inspection of the engine should also be considered before establishing the probability of an engine loss.

3) Other factors that were analyzed were a) reduced thrust from one engine throughout the flight, b) early rotation at an airspeed 8 kt less than the value proper to the actual airplane weight, c) loss of an engine in thrust reversal mode, and d) combinations of 1, 2, and 3. Each of these conditions, if they actually occurred, could not of themselves or in combination provide a reasonable explanation of the accident.

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