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Aircraft Accident Flight Path Simulation and Animation

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During 1987, Northwest Airlines Flight 255 crashed in Detroit in the summer, and Continental Airlines Flight 1713 crashed in Denver in the winter. This article will describe the reconstruction, simulation, and animation of the time dependent flight path for each accident through a process known as forensic engineering. Forensic engineering is the application of scientific and engineering knowledge to legal matters, such as accident reconstruction. The flight paths were reconstructed as an aid in visualizing the sequence of events and the factors involved in each accident.

Nomenclature

a_n = normal acceleration, ft/s^2
$C_{l\max}$ = maximum lift coefficient
D = aircraft drag, lb
D_r = engine ram drag, lb
g = gravitatonal acceleration constant, 32.2 ft/s^2
L = aircraft lift, lb
$L_{\max}$ = $C_{l\max}(0.5\ \rho V^2)S_{\text{ref}}$
S_{ref} = wing planform area, ft^2
T_g = engine gross thrust, lb
V = aircraft true velocity, ft/s
W = weight, lb
X = horizontal distance, ft
Z = aircraft altitude, ft
Z_{sr} = radar altimeter, ft
α = angle of attack, deg
γ = flight path angle, deg
$\dot{\gamma}$ = flight path angle time rate of change, rad/s
δ = thrust inclination angle, deg
μ = rolling coefficient of friction during ground roll
ξ = angle between aircraft heading and wind heading, deg
ρ = air mass density, lb-s/ft^4
ρ_a = standard calibration density
ρ_{atm} = ambient density
Ψ = heading angle, deg

Introduction

THE flight paths were reconstructed using data from several sources. The primary source of information was from the flight data recorder (FDR), the cockpit voice recorder (CVR), and photographs and drawings. These data were supplemented by solving the equations of motion to study the effect of changing various input parameters. In addition, information from the National Transportation Safety Board (NTSB) accident report, photographs, maps, and drawings were used to provide external cues as to the aircraft position and attitude in space and time.

Dietenberger et al.[1] and Luers and Dietenberger[2] provide an excellent background for aircraft accident reconstruction techniques similar to those used in this work. The use of FDR information as direct input to the aircraft equations of motion was used in the analysis of the Pan Am Flight 759 accident of July 9, 1982.[1] The second accident, an Arrow Air DC-8-63 on December 11, 1985, used a two-part approach. First, a takeoff simulation was used to study the sensitivity of various factors as potential causes of the accident. Then, the aircraft trajectory was established by solving the aircraft equations of motion.

The purpose of the reconstructions was not to determine blame nor degree of responsibility in each accident, but to provide a visual tool for understanding the motions of the aircraft during the takeoff roll, rotation, and climbing flight. Edited versions of the animated flight paths were produced in video and used for courtroom demonstrations by attorney, R. F. Schaden of Schaden, Lampert, and Lampert; Denver, Colorado, who represented a group of the plaintiffs in each of the legal cases.

Accident Flight Path Reconstruction

There are five stages in the process of aircraft flight path reconstruction: 1) geometry modeling, 2) motion specification/simulation, 3) image rendering, 4) animation, and 5) video production.

1) Geometry Modeling

The first stage consists of developing the geometric model of the object, that is defining a grid or mesh around the exterior of the object. This is done by generating either a wire-frame or surfaced model rendition of the geometry.

2) Motion Specification/Simulation

The purpose of simulation is to model the behavior of a real world system.[3] Modeling is the representation of a system in a mathematical form that is suitable for demonstrating the behavior of the system. Simulation is the process of subjecting the model to various inputs to observe its behavior and explore the nature of the results that might be obtained from the real world system. To study the behavior of a system, a set of assumptions in the form of a mathematical model are used. The computer is used to evaluate the model numerically. The state of the system is that collection of variables necessary to describe a system at a particular point in time. The simulation of the flight of an aircraft is known as a continuous system, i.e., the state variables change continuously with time.

3) Image Rendering

The process of producing or rendering a realistic image by removing hidden surfaces and adding effects such as shading, shadows, transparency, and texture. High vs low fidelity image rendering are considerations based on the processing power of the workstation being used.

4) Animation

Either the "real-time" or "frame-by-frame" animation mode of production is used.[4] In real-time animation, the scene is

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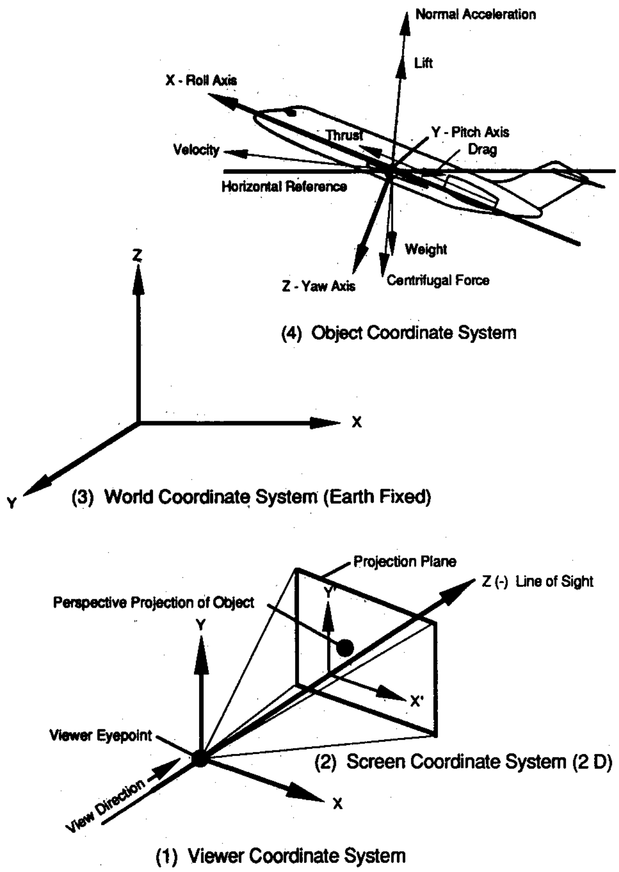


Fig. 1 Computer graphics coordinate systems.

developed and displayed in real time, thus limiting the fidelity of the rendition. The image must be displayed at a rate greater than 15 frames/s to reduce flicker, or the illusion of continuous movement will break down. The constraints are imposed by the workstation's cycle speed, storage capabilities, word length, and instruction set. The system performance is defined by the 1) frame rate, 2) polygon count, and 3) scene content.

The advantage of real-time animation is that the scene content may be easily varied by varying the camera position at will. The disadvantage is that the image fidelity and realism is degraded to meet the 15 frames/s display rate within the workstation's performance capability.

In frame-by-frame animation, the images are very complex and realistic. These frames are rendered, recorded on an individual basis, and displayed at a rate of 30 or 60 frames/s. The individual images may take full advantage of the rendering capabilities of the graphics software being used. The advantage of frame-by-frame animation is the realistic image (high fidelity), while the disadvantage is that the scene content and format must be fixed to produce the video sequence. In the process of animation, "key frames" are used to specify the starting or ending point for a gradual movement or change. The process of "tweening" is then used to generate additional frames between the key frames by either linear or spline interpolation.

5) Video Production

Video production may take one of two forms after the data file has been generated. The video may tape directly from the workstation monitor. This is acceptable if the monitor resolution is high. An alternative for frame-by-frame animation is the use of a video animation controller to record the graphic images to videotape on a single frame basis. In addition, the use of a video frame grabber makes it possible to sequentially digitize prerecorded video.

Coordinate Systems

The computer graphics display of a geometric model is developed by applying a sequence of translational and rotational transformations to the point data set defining the model. The sequence consists of a set of matrices establishing the view orientation, followed by the projection transformation matrix. These transformation matrices are based on the use of homogeneous coordinates.[5] Homogeneous coordinates are used to relate and transform the displayed objects in the "world" coordinate system. Four coordinate systems (Fig. 1) are used during the process of simulation,[6] including 1) world (global), 2) object, 3) observer, and 4) screen.

1) World (global): Used to relate the positions of all objects displayed in the scene, as well as to orient the camera (observer). The world coordinate system is considered to be the "absolute" coordinate system. In the case of accident reconstruction, it is the ground reference system.

2) Object: Used to define the surface geometry of the objects that will be displayed in the scene. The surface coordinates are used to define a model that is rendered either as a wire frame or surface model. The object coordinate system is also used to reference the position of the object in the world coordinate system. The origin of this coordinate system is positioned at the c.g. of the aircraft, and its relation to the world coordinate system is a state vector containing the three translational coordinates, X (longitudinal), Y (lateral), and Z (vertical), as well as the Euler angles ϕ (roll), θ (pitch), and Ψ (heading).

3) Eye (camera) (observer): Used to orient the camera, or scene observer, position, the observation or viewing direction, and the aperture. These parameters are similar to the adjustments that a photographer must make when photographing, filming, or taping a scene. The viewpoint is the location of the camera relative to the object being filmed, the viewing direction is determined by the orientation of the camera lens relative to the scene, and the aperture is the lens that determines how much of the scene will be seen.

4) Screen: Used to display the two-dimensional projection mapping of the three-dimensional objects being observed. May display either an orthographic (axonometric) or a perspective (photograph) mapping. The screen coordinate system is considered to be the relative coordinate system.

Continental Airlines Flight 1713: November 15, 1987

The Continental Flight 1713 accident occurred in the winter of 1987 in Denver at the Stapleton Airport, NTSB.[7] On November 15, 1987, Continental Airlines, Inc., Flight 1713 was cleared to takeoff following a delay of 27 min after deicing. Following a rapid rotation after the takeoff roll, the aircraft crashed off the right side of runway 35L. Two crew members, one flight attendant, and twenty-five passengers sustained fatal injuries. Two flight attendants and fifty-two passengers survived.

Cause

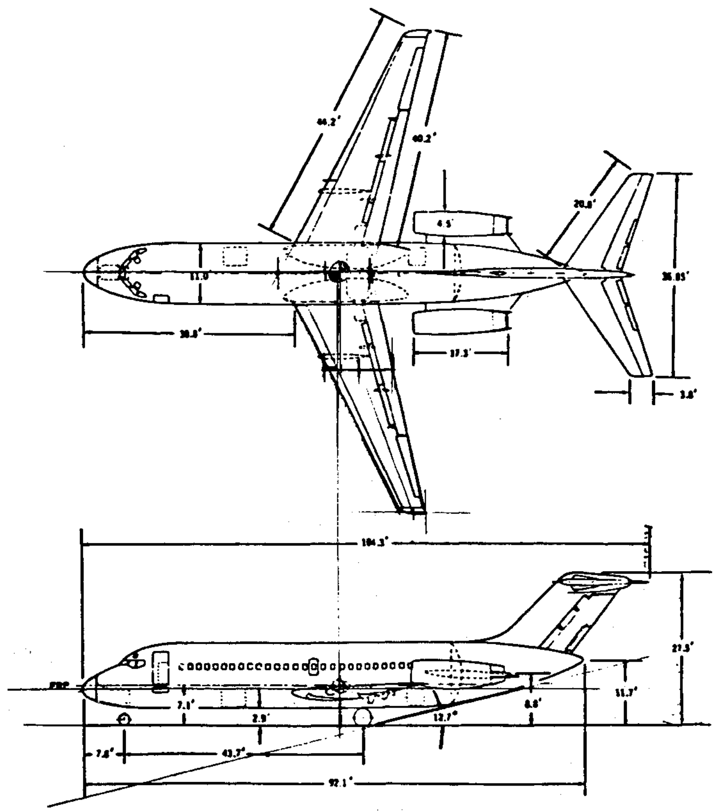
The NTSB[7] determined that the probable cause of the accident was 1) the failure to have the aircraft deiced a second time before takeoff that led to upper wing surface contamination and 2) a loss of control during the rapid takeoff rotation.

Table 1 Flight 1713 time history

Event	Time, s
Initiate takeoff	0.0
100 kt	10.4
V_1	21.8
Vr	24.2
Liftoff	28.0
Positive climb rate	29.8
Impact	33.8

MODEL DC-8 SERIES 10 : GENERAL CHARACTERISTICS

Wing Area	Sq Ft	934.3
Wing Span	Ft	89.3
Aspect Ratio		8.55
Sweep @ Quarter Chord	Deg	24.0
Length, Overall	Ft	104.3
Fuselage Width, Maximum	In	131.6



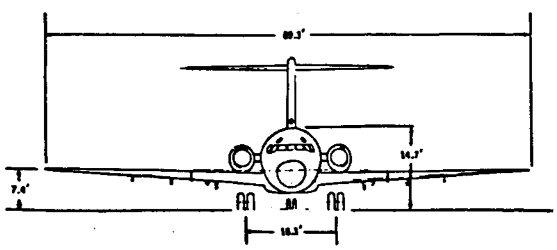


Fig. 2 McDonnell Douglas DC-9 Series 10.

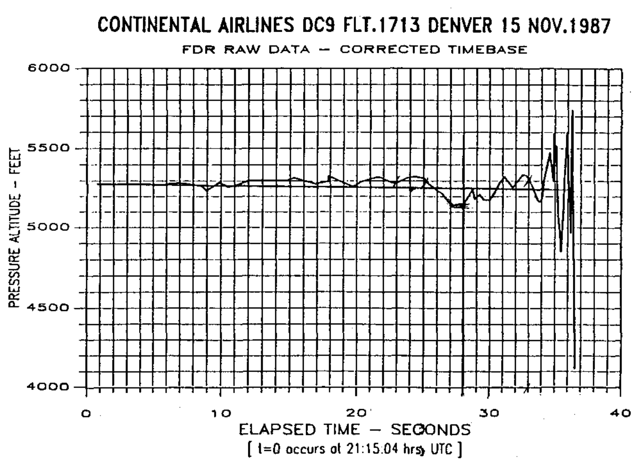


Fig. 3 Continental 1713 FDR pressure altitude.

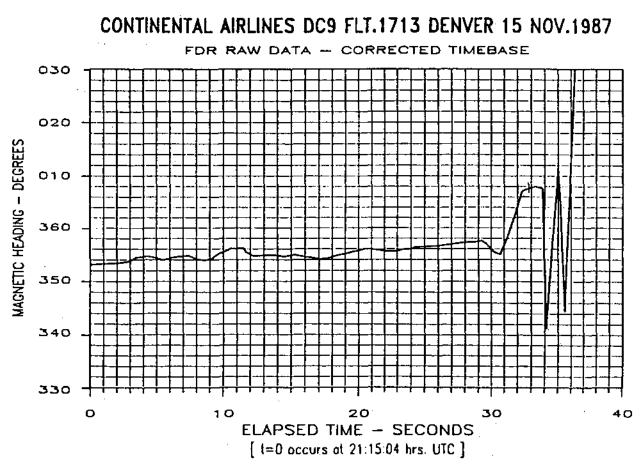


Fig. 4 Continental 1713 FDR magnetic heading.

Location

The accident occurred on runway 35L of the Stapleton Airport in Denver, Colorado. The runway is 5330 ft above sea level.

Aircraft

The aircraft was the McDonnell Douglas DC-9 Series 10 (Fig. 2). This was the first version in the DC-9 series and did not utilize leading-edge slats.[8,9] The aircraft, N626TX, was delivered in June of 1966. The trailing edge flaps were set at 10 deg for takeoff.

Wing span	=	89 ft 4 in.
Wing aspect ratio	=	8.55
Fuselage length	=	104 ft 4 in.
Take gross weight	=	86,056 lb.
Engines	=	Pratt & Whitney JT8D-7 turbofans (two)

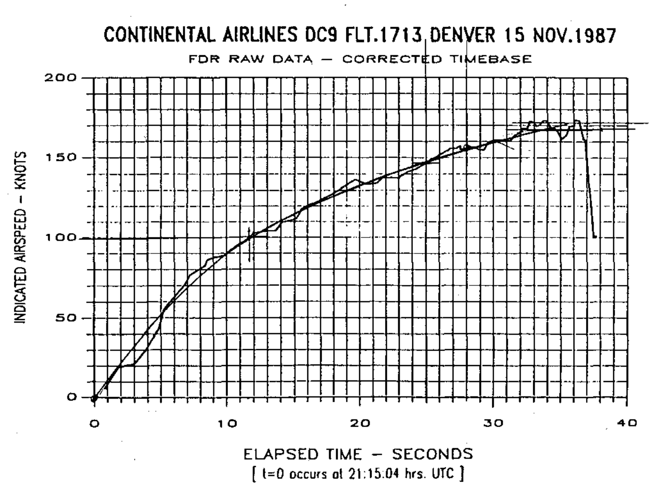


Fig. 5 Continental 1713 FDR indicated airspeed.

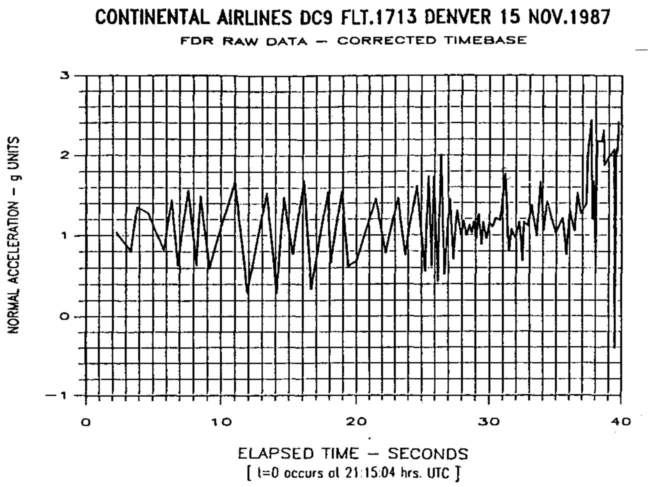


Fig. 6 Continental 1713 FDR normal acceleration.

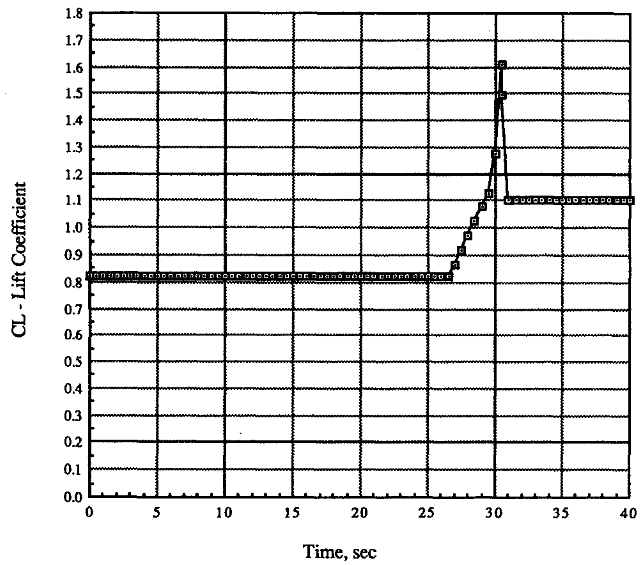


Fig. 9 Continental 1713 lift coefficient time history.

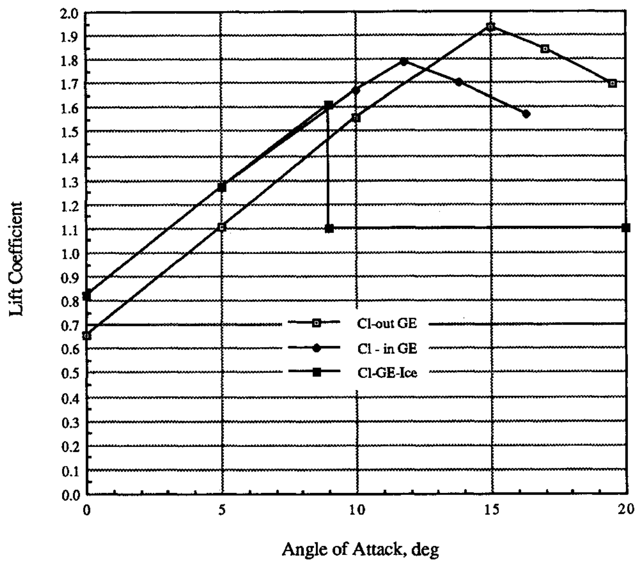


Fig. 7 Continental 1713 wing lift coefficients.

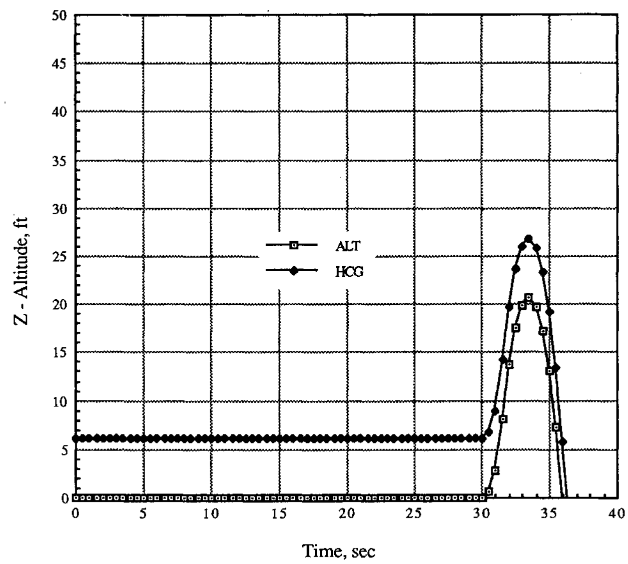


Fig. 10 Continental 1713 altitude time history.

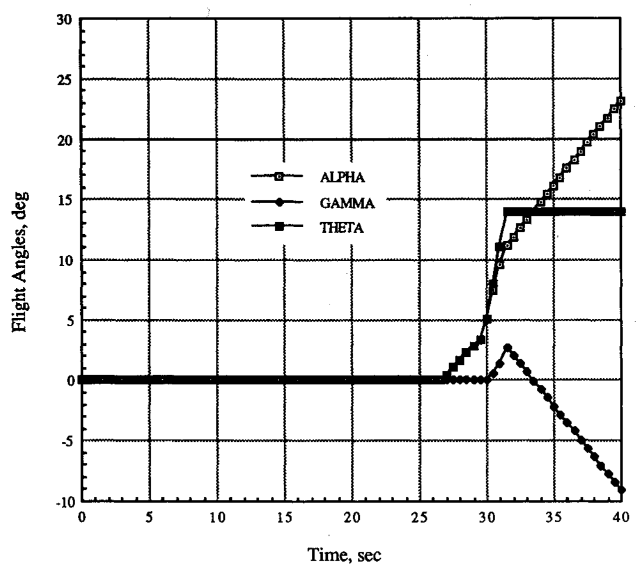


Fig. 8 Continental 1713 pitch, angle of attack, and flight path angle time histories.

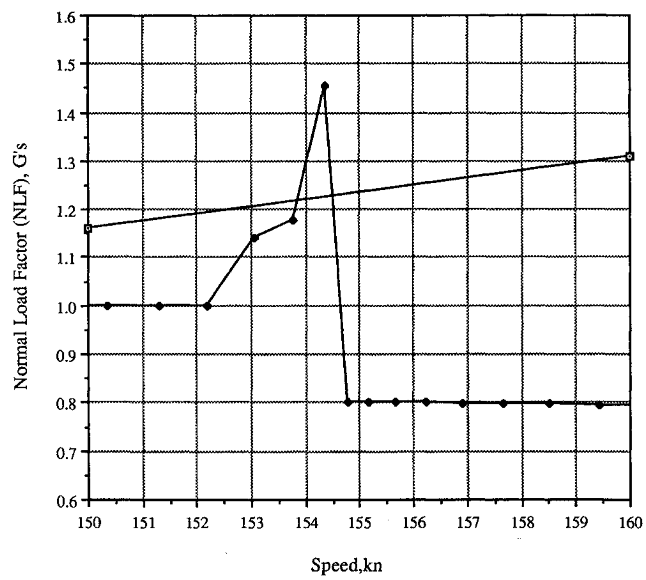


Fig. 11 Continental 1713 normal load factor time history.

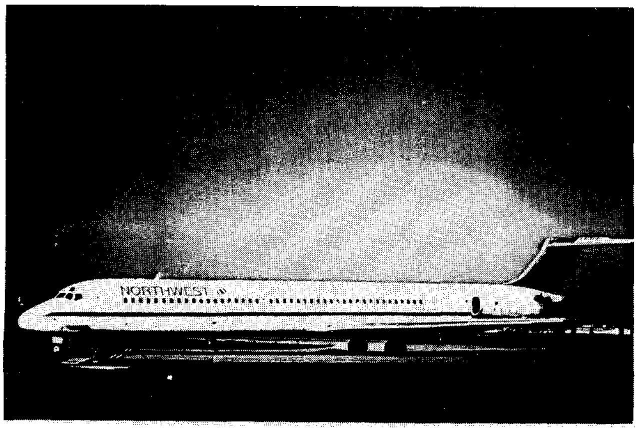


Fig. 12 McDonnell Douglas DC-9-82 (MD-82).

Weather

Light to moderate snow conditions existed at the Stapleton Airport which is 5330 ft above sea level. The air temperature was 28°F, with a 33°F surface temperature. The wind was 14 kt at 030, with gusts to 20 kt. Approximately 2.75 in. of snow had fallen before the accident, which occurred at 2:14:33 p.m. MST. The weather conditions were such that the wings required deicing. The takeoff did not commence until 27 min after the deicing, 7 min past the maximum recommended time of 20 min before requiring deicing. The aircraft stalled during the rotation phase of the liftoff and subsequently crashed.

NTSB Data

The NTSB determined from ground scar information that the roll angle at impact was about 38 deg and that a net altitude gain of at least 20 ft was attained. In addition, an average flight path angle γ of -6 deg was required for the wing and fuselage to align with the wingtip and fuselage ground scars. The NTSB also developed the following event history from the CVR (Table 1).

The two sources of aircraft flight data used were the CVR and the FDR. Continental Flight 1713 used an older FDR which was limited to the measurement of four flight parameters. These included 1) pressure altitude, ft; 2) magnetic heading, deg; 3) indicated airspeed, kt; and 4) normal acceleration, g.

The time traces for these four parameters are shown in Figs. 3–6. The only trace that was of value in reconstructing the aircraft motion during the flight path history was the airspeed. The pressure altitude was not used because of inaccuracy near the ground. The normal acceleration is seen to be extremely noisy during the ground run to liftoff at 28 s. Attempts to integrate the signal past this point to obtain the altitude time history were unsuccessful.

Flight Equations of Motion

Consequentially, takeoff ground run, rotation, and liftoff equations of motion (EOM) were used to develop the two-dimensional flight path in the X-Z plane. Since the FDR did not record roll information, and no other reliable information was available, only a two-dimensional simulation was developed. The state variable included γ, Z, and X. These EOM were obtained from Foss.[10] The equations cover the flight path for the ground run portion of the flight to rotation and liftoff, the transition to steady climb, and then steady climb (Fig. 7).

Ground Roll: ($\gamma = 0$)

$$\dot{V} = (g/W)[T_g \cos(\alpha + \delta) - D - D_r - \mu(F_w)] \quad (1)$$

Flight: ($\gamma > 0$)

$$\dot{V} = (g/W)[T_g \cos(\alpha + \delta) - D - D_r - W \sin(\gamma)] \quad (2)$$

$$\dot{\gamma} = (g/VW)[T_g \sin(\alpha + \delta) + L - W \cos(\gamma)] \quad (3)$$

$$\dot{Z} = V \sin(\gamma) \quad (4)$$

$$\dot{X} = V \cos(\gamma) \quad (5)$$

The aircraft pitch angle θ (Fig. 1) is related to γ and α:

$$\theta = \gamma + \alpha \quad (6)$$

During the rotation phase of the flight, the aircraft is in a flight path that results in a centrifugal force due to the normal acceleration (Fig. 1). This results in the centrifugal force adding to the weight so that the wing lift requirements are increased. This force is reduced to zero when the steady climb condition is achieved. The normal acceleration (normal to the velocity vector) is

$$a_n = V\dot{\gamma} \quad (7)$$

so that the centrifugal force (CF) is

$$\text{CF} = [(WV\dot{\gamma})/g] \quad (8)$$

The normal load factor (NLF), expressed in units of g, is defined as

$$\text{NLF} = [W \cos(\gamma) + \text{CF}]/W = [W \cos(\gamma) + (WV\dot{\gamma}/g)]/W$$

or

$$\text{NLF} = [\cos(\gamma)] + (V\dot{\gamma}/g) \text{ (simulation)}$$
$$\text{NLF} \approx 1 + (V\dot{\gamma}/g) \quad (9)$$

The normal acceleration measured by the FDR is in the aircraft coordinate system (Fig. 1), so that it is actually measuring

$$a_n^* = a_n \cos(\alpha) \quad (10)$$

The normal load factor is obtained from the FDR data then as

$$\text{NLF} = 1 + a_n^*/[g \cos(\alpha)] \quad (11)$$

The NLF is balanced against the maximum allowable values, NLF*, which result from the maximum wing lift coefficient:

$$\text{NLF}^* = L_{\max}/W \quad (12)$$

Values for the power on $C_{l\max}$, were determined for the clean wing conditions to be

Wing clean (out of ground effect): $C_{l\max} = 1.94$

Wing clean (in ground effect): $C_{l\max} = 1.79$

The effect of ice on the wing $C_{l\max}$ was determined using the technique described in Ref. 11. An accumulated liquid water equivalent of 0.032 in. was determined to have fallen at the time of the accident. This was equal to an ice thickness of 0.36 in., resulting in a nondimensional roughness height, based on the mean aerodynamic chord (MAC) of 141.5 in. of 0.000254. The effect of a coat of ice on the wing upper surface results in a surface texture of considerable roughness,

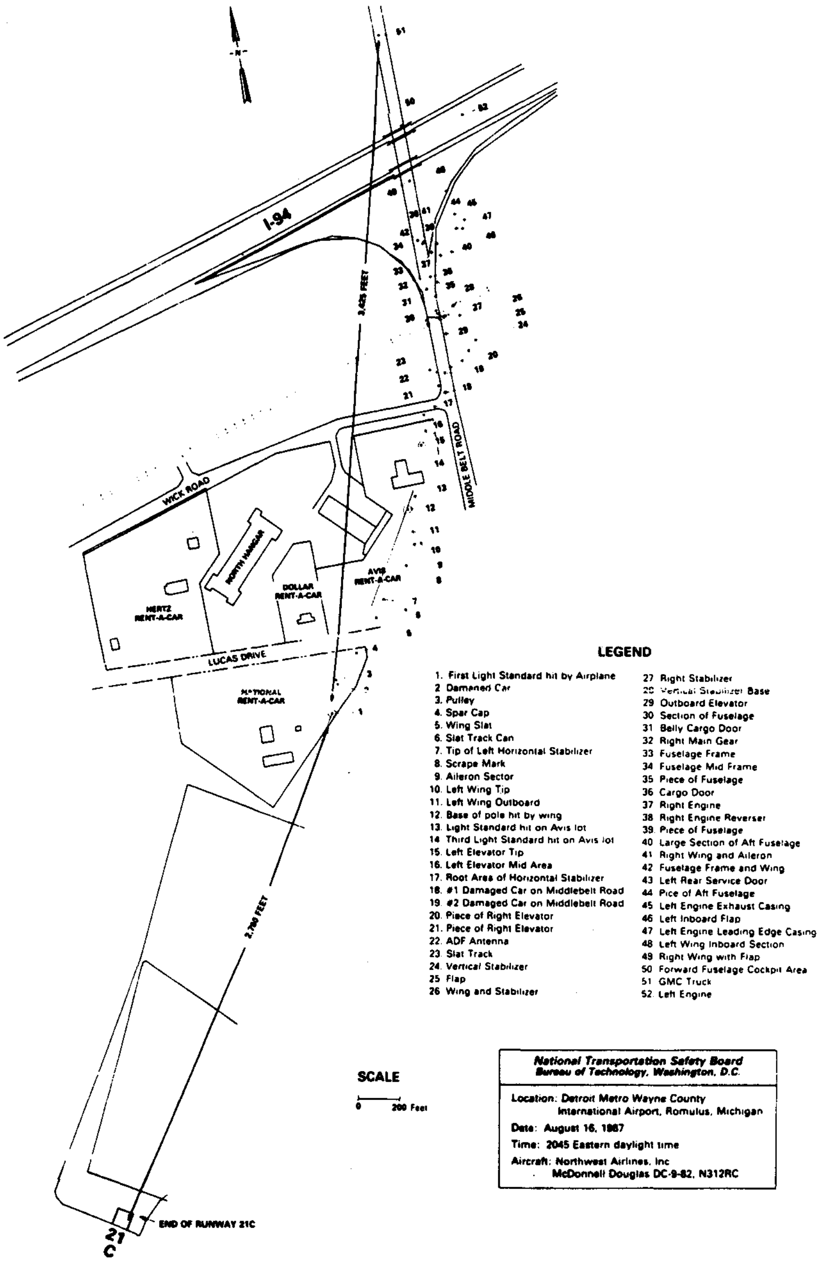


Fig. 13 Northwest 255 scatter diagram.

Table 2 Flight 255 time history

Sound no.	Event	Time, s
1	First pole impact	0
2	Wing horizontal/stabilizer	0.4
3	Second pole impact	3.37
4	Avis building/front/port wing	3.81
5	Avis building/rear/port wing	3.99
6	Avis building/rear tail	4.17
7	Third pole impact	4.52
8	Ground impact	5.71

resulting in an increase in drag and stall speed (i.e., a decrease in $C_{l\max}$). Assuming that the ice covered approximately 70% of the wing upper surface, the maximum lift coefficient was found to be

$$\text{Wing/ice (in ground effect): } C_{l\max} = 1.61$$

The NTSB[7] determined that the aircraft attained θ of 14 deg, while the aircraft was close to the ground, which is 8 deg greater then the normal value of 6 deg. Furthermore, the NTSB determined that the pitch rate $\dot{\theta}$ was over 6 deg/s, which is twice the rate recommended. This time history trace, which reflects the pilot control of the aircraft, was used as the input to the model since there is not a separate equation for the control input.

Two-Dimensional 1713 Flight Path

Using the pitch $\theta(t)$ history, the lift (α) and the drag (α) coefficient curves including the effect of ice, and a time domain program based on the equations of motion, the flight path was determined from the rollout to liftoff and subsequent ground impact. The EOM were integrated forward in time to obtain the time dependent state vector describing the aircraft position and attitude.

After applying varying amounts of ice to the wings to vary the aerodynamic characteristics, a flight path was obtained that corresponded to the available external cues. Figure 7 shows the lift coefficient curves for a clean wing out of ground effect ($C_{l\max} = 1.94$), a clean wing in ground effect ($C_{l\max} = 1.79$), and a contaminated wing in ground effect ($C_{l\max} = 1.61$). It was determined that wing ice induced stall during rotation was the most plausible explanation for the accident.

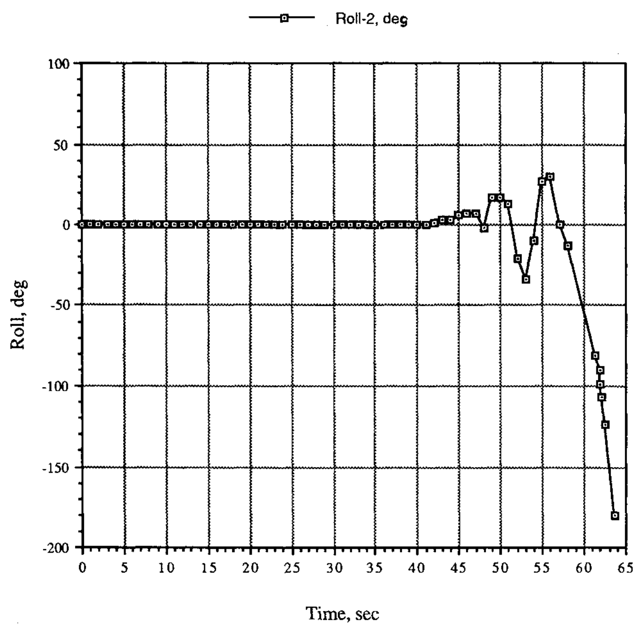


Fig. 14 Northwest 255 CG altitude time history.

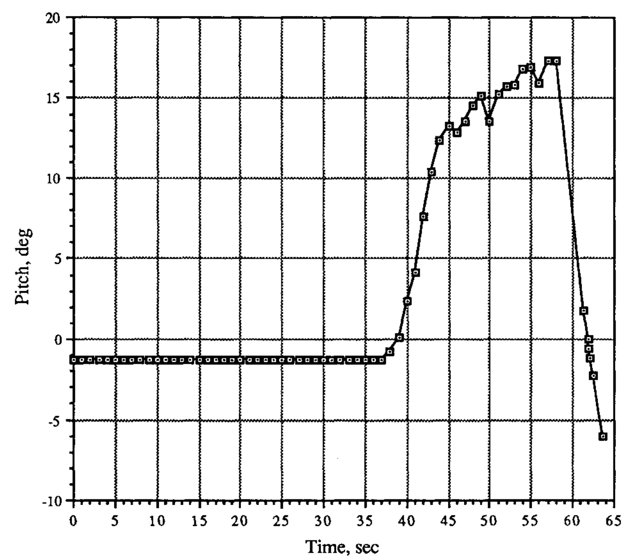


Fig. 15 Northwest 255 pitch angle time history.

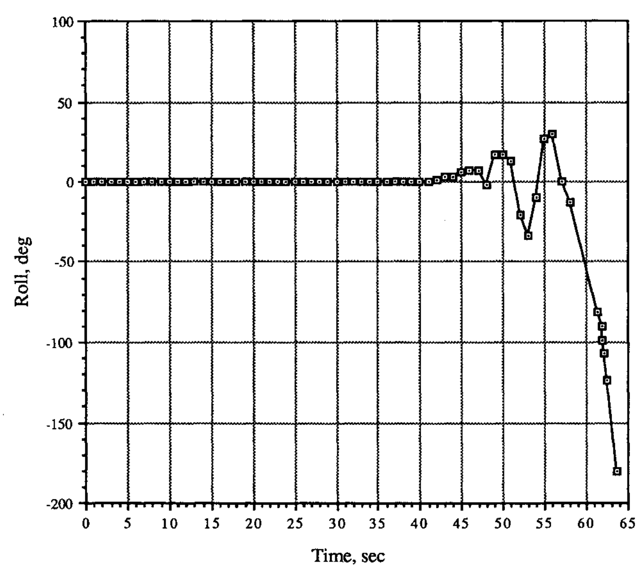


Fig. 16 Northwest 255 roll angle time history.

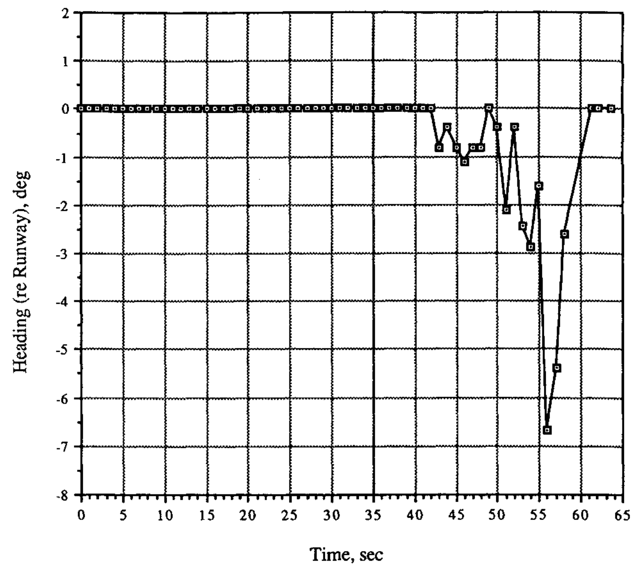


Fig. 17 Northwest 255 heading angle time history.

θ, as determined by the NTSB, α, and γ time histories are shown in Fig. 8. The angle of attack continues to increase after the pitch angle has reached its maximum value. The flight path angle initially increases to a value of 3 deg, and then decreases, indicating downward flight.

The lift coefficient time history (Fig. 9) shows an increase to the maximum value of 1.61 at 31 s, at which point the wing stalls and the lift coefficient decreases to a value of 1.1. The altitude to the main gear wheel bottom and c.g. time history is shown in Fig. 10. The bottom of the main gear wheels rises to an altitude of about 20 ft before the impact at about 36 s. The normal load factor (NLF) (Fig. 11) shows that the peak from the simulation is higher than the limit based on $C_{l_{max}} = 1.61$, indicating wing stall as assumed. A maximum NLF of 1.4 was reported by the NTSB[7] which agrees with these results.

Northwest Airlines Flight 255: August 16, 1987

The Northwest Flight 255 accident occurred during the summer of 1987 in Detroit at the Detroit Metropolitan Airport, NTSB.[12] On August 16, 1987, the flight commenced without the wing slats and flaps being in the deployed position for takeoff. In addition, the Central Aural Warning system (CAWS) malfunctioned so that the flight crew was unaware of the improper takeoff configuration. The flight crew of 2, 4 flight attendants, 148 passengers, and 2 persons on the ground were fatally injured. One passenger, a 4-yr-old child, survived.

The aircraft proceeded through the ground roll and rotation phases to liftoff. Although the aircraft was climbing at a very low rate of climb (ROC), the aircraft struck a light standard in a parking lot off the end of the runway, losing approximately 17 ft of its port wingtip. The aircraft subsequently struck a second light standard and then a building and crashed.

Cause

The NTSB[7] determined that the probable cause of the accident was 1) the wing flaps and slats were not extended to the proper position for takeoff and 2) the CVR revealed no evidence that the crew received a warning of the airplane's improper takeoff configuration from the CAWS.

Location

The accident occurred on runway 3C of the Detroit Metropolitan Airport in Romulus, Michigan. The runway is 635 ft above sea level on a magnetic heading of 31.43 deg. The runway is 200 ft wide with a length of 8500 ft.

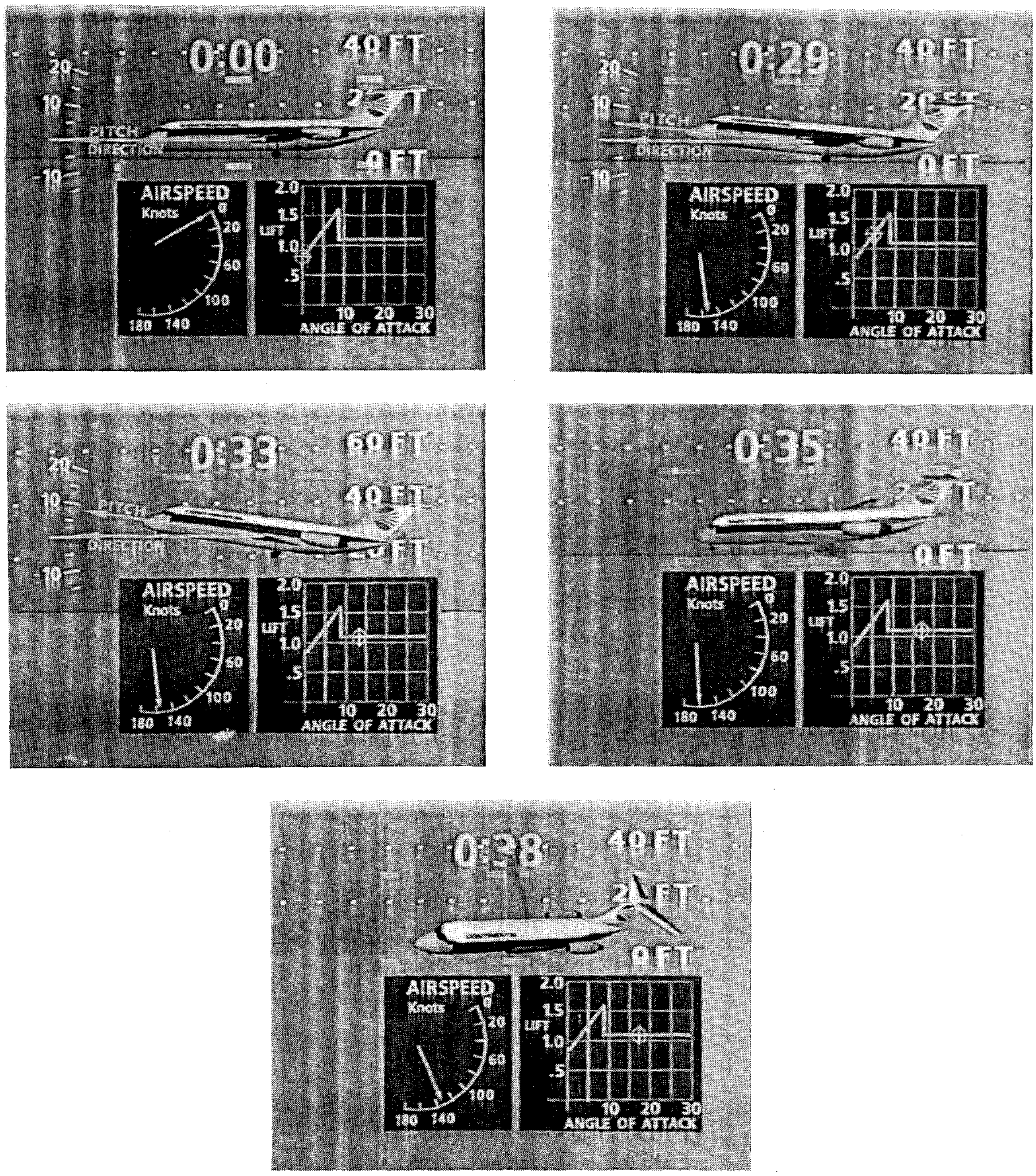


Fig. 18 Continental 1713 accident video animation sequence.

Aircraft

The aircraft was the McDonnell Douglas DC-9-82 (MD-82), which is shown in Fig. 12 1 day before the accident. The wing configuration includes slats and flaps. The aircraft was delivered December 8, 1982.

Wing span	=	107 ft 10 in.
Wing aspect ratio	=	9.62
Fuselage length	=	135 ft 6 in.
Take gross weight	=	144,000 lb
Engines	=	Pratt & Whitney JT8D-217 turbofans (two)

Weather

The wind was from the left of the runway at a heading of 280 deg and a speed of 12 kt. At the time of the accident, 2046 (8:46 p.m.), the weather was 79°F, scattered clouds, and a 4500-ft. ceiling with no precipitation.

NTSB Data

An overview of the runway and crash site shows the sequence of events during the crash. The scatter diagram (Fig. 13) locates in *XY* coordinates the ground location of pieces of the aircraft and objects struck by the aircraft as it was crashing. For example, no. 1 is the first light standard hit by the aircraft wing, no. 12 is the base of the second light standard struck, no. 13 is the location of the second light standard, and no. 14 is the third light standard struck.

After impacting the first pole severing 17–18 ft of the port wing (about one-third), the wingtip rotated up and backwards impacting the left horizontal stabilizer. Fuel spilling from the left wing was ingested by the left engine and caught fire.

The aircraft was observed to bank to the left after the fire appeared and was engulfed in flames. The tip of the horizontal stabilizer is at no. 7, and nos. 10 and 11 locate the left wingtip and outboard portion of the left wing. The light pole was 2760 ft from the departure end of runway 3C, and 100 ft to the right of the runway centerline.

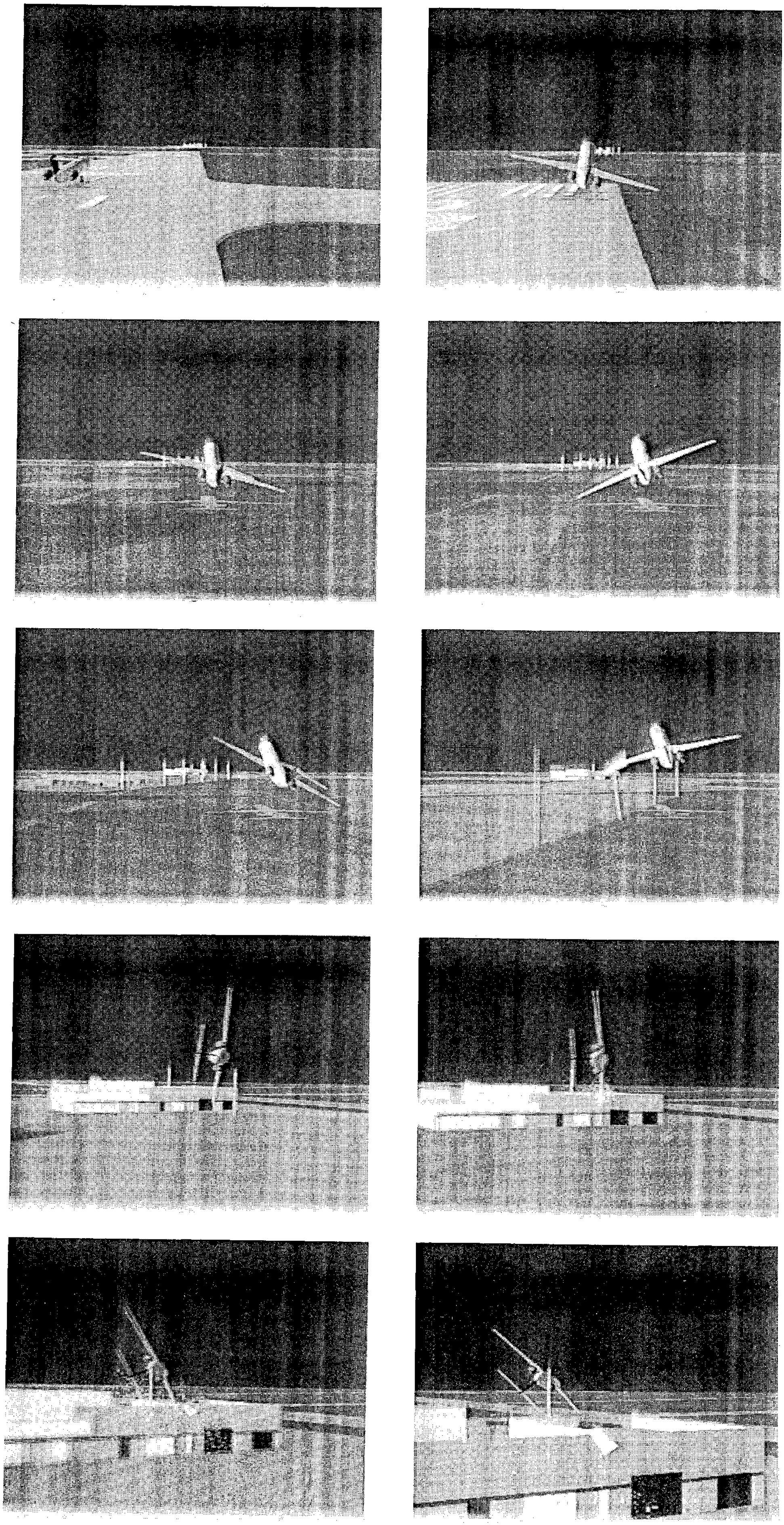


Fig. 19 Northwest 255 accident video animation sequence.

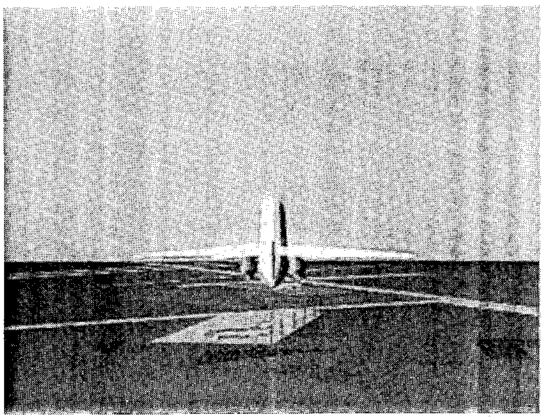


Fig. 20 Northwest 255 safe flight video animation scene.

Motion Specification

The FDR data were used for the reconstruction of the three-dimensional flight path history. In this case, the state variables included the horizontal lateral and longitudinal ground distances X and Y, altitude Z, pitch angle θ, roll angle ϕ, and yaw angle Ψ. A three-dimensional inertial coordinate system was embedded in the ground with the origin at the point of the beginning of the takeoff roll. The X axis was in the longitudinal direction, Y axis in the lateral direction, and the Z axis in the vertical direction. The object coordinate system was embedded in the aircraft with the origin located at the aircraft c.g. Direct measurements, with corrections, were used to develop the position and attitude state variable as a function of time. However, the FDR malfunctioned at the point where the wing struck the pole and stopped recording. In order to develop the entire path to ground impact, data from an aerial photograph were used to create X-Y ground and airport terrain data. Architects drawings of the AVIS rental car building that was struck, as well as photographs of both the damaged building and poles were used.

First Pole Impact

The impact damage to the first pole in the National Car Rental parking lot indicated that the wing of the aircraft was 37.67 ft above the ground level. With this information, the radar altitude, pitch and roll data, and the aircraft geometry, the exact orientation and altitude of the aircraft c.g. was determined. The radar altitude measures the slant range from the transponder, on the bottom of the aircraft to the ground. The distance required for the motion specification is the vertical distance from the c.g. to the ground:

$$Z'_{\text{agl}} = (Z_{\text{sr}} - 7.63)(\cos\phi) - [(28.6\sin\theta - 2.12)](\cos\theta\cos\phi) + [9.0 + 0.1862(\theta) - 0.0056196(\theta^2)](\cos\phi) \quad (13)$$

From the data, the following were the aircraft orientation and altitude at the time of first pole impact:

Time	= 57.45 s
Roll angle	= 12.5 deg (left wing down)
Pitch angle	= 17.3 deg (nose up)
Z_{sr}	= 52.78 ft
Z_{CG}	= 46.42 ft

X, Y-Ground Distances

The X-longitudinal and Y-lateral ground distances were determined using the ground speed, heading, and wind data. The ground speed is determined from the indicated airspeed (U_{IAS}) from the FDR:

$$U_{\text{CAS}} = U_{\text{IAS}} - 2.0 = \text{Calibrated airspeed, kt} \quad (14)$$

$$U_{\text{TAS}} = U_{\text{CAS}}\sqrt{\rho_{\text{atm}}/\rho_a}\text{, kt} = 1.032U_{\text{CAS}}\text{, kt (Detroit)} = \text{True airspeed} \quad (15)$$

The true airspeed is corrected to ground speed using Ψ, the wind speed, and direction:

$$U_x = U\text{TAS}(\cos\Psi) + U_w(\sin\xi) = X\text{-longitudinal direction velocity component, kt (parallel to runway centerline)} \quad (16)$$

Tailwind: $U_x > U_{\text{TAS}}$

Headwind: $U_x < U_{\text{TAS}}$

$$U_y = U_{\text{TAS}}(\sin\Psi) + U_w(\cos\xi) = Y\text{-lateral direction velocity component, kt (perpendicular to runway)} \quad (17)$$

Then

$$V_x = 1.688\,U_x \qquad V_y = 1.688\,U_y \quad = \text{velocity, fps} \quad (18)$$

$$X = \int (V_x)\,dt \qquad Y = \int (V_y)\,dt \quad (19)$$

ξ = longitudinal and lateral ground distances, ft

Cockpit Voice Recorder

The cockpit voice recorder provided aural cues from the timing of the impact sounds, with the first pole impact as the first impact sound. A total of eight impacts can be heard on the CVR (Table 2).

Three-Dimensional 255 Flight Path

The FDR data were used for the development of the flight path model up to the first pole impact. A three-dimensional inertial coordinate system was embedded in the ground with the origin at the point of the beginning of the takeoff roll. The X axis was in the longitudinal direction, Y axis in the lateral direction, and the Z axis in the vertical direction. Direct measurements, with corrections, were used to develop the position and attitude state variable as a function of time.

The FDR failed after the first pole impact so that it was necessary to use data from the other evidence to recreate the flight path past this point. In order to develop the entire three-dimensional flight path, data from an aerial photograph were used to create X-Y ground and airport terrain data. Architects drawings of the building that was struck, as well as photographs of the damaged buildings and poles, were also used.

In addition, 1/150 scale models of the aircraft, poles, and the Avis building were used to determine the relational geometries to complete the flight path. The scale aircraft model was positioned at the first pole and at the various impact points with the Avis building. The aircraft orientation was time correlated using the CVR recording which gave impact event sounds. The X, Y location was determined from the aerial photograph, while the altitude, pitch, roll, and yaw angles were determined using the aircraft model. The final flight path is defined by three translations (X, Y, and Z), and three rotations (θ, ϕ, and Ψ). Z, θ, ϕ, and Ψ, are shown in Figs. 14–17.

Video Production

After the development of each of the flight paths, video animations were produced by the Z-Axis Corporation of Aurora, Colorado. Geometry data base models of each aircraft were developed, in addition to models of the runway and airport terrain. These geometry models were then manipulated using the homogeneous coordinate technique to vary the scene observer viewpoint and view direction. In combination with the time dependent state position and attitude variable, video animations were produced.

Both of the video animations were generated by the Z-Axis Corp. on a Bosch 4500 Video Graphics System. This system includes the software to do the modeling and rendering, as well as the hardware for display and video production. The system, which does frame-by frame animation, displays at a rate of 30 frames/s. Since the motion specification files were developed at 1-s intervals, they were used as the key frames and linear interpolation was used to tween the intermediate 29 frames. The maximum polygon count was approximately 2000 for each of the videos produced.

Continental 1713 Video

The Continental 1713 accident video animation sequence is shown in Fig. 18 at flight times of 0, 29, 33, and 35 s after roll out. The time in seconds is displayed at the top, in addition to an altitude scale (ft), pitch angle (deg), airspeed (kt), and the lift coefficient—alpha curve with the cursor indicating the lift coefficient at that instance in time.

Northwest 255 Video

The Northwest 255 accident video animation sequence is shown in Fig. 19 beginning at the time of liftoff. The first pole impact occurs in scene no. 6, with the wing striking the front of the Avis building in scene no. 8. Scene no. 9 shows the wing striking the rear of the Avis building, while scene no. 10 is just before ground impact. A safe flight is depicted in Fig. 20 showing the aircraft at an altitude of about 600 ft while passing over the parking lot and Avis building.

Conclusions

The process of aircraft accident reconstruction for forensic engineering will require the use of several techniques depending on the evidence that is available. The most important will be the data from the FDR and the CVR. Additional evidence will be the scatter diagram, damage photographs, ground charts, and aerial photographs. This information, coupled with the aircraft equations of motion, provide the tools for reconstructing the aircraft trajectory. The use of high level computer graphics to depict the aircraft trajectory in a real time animation allows the jury to view a complex set of events in a fashion that will allow them to understand what is occurring.

The problems involved with using this technique in the courtroom are that it is expensive in terms of both time and money. Computer graphics technical problems include image resolution issues for realistic looking images, frame rate, and polygon count.

The use of an existing flight simulator is another technique that can be used for the accident investigation. However, the simulation will only model the aircraft characteristics that are required in normal flight. The simulator will not usually model an aircraft that has been damaged such as NW 155, or experiences a natural phenomenon like the wing icing that occurred on Continental 1713. The other problem is that the accident investigator must have access to the simulator.

Both of the computer graphics animations were generated using the frame-by-frame animation technique. While this technique has the advantage of rendering high resolution images, it clearly has the disadvantage of the large amount of time to render each individual frame and, more importantly, leaving no margin for error in selecting the parameters required for the scene generation. If the observer viewpoint, for example, is not quite right, the parameters must be changed and the frames rendered over again. This technique is thus limited to scenes of a few seconds in duration.

In contrast, present high-level computer graphics workstations, such as the Silicon Graphics IRIS™, are capable of rendering fairly high-resolution images in real time at realistic frame rates. In addition, the observer viewpoint location and direction may be changed in real time. The limitation to this approach will depend on the number of polygons that can be displayed and manipulated, which will depend on the power of the particular workstation being used.

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