NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Washington, D.C. 20594

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Aircraft Performance - Addendum #1

Addendum to Group Chairman's Aircraft Performance Study
by John O'Callaghan

A. ACCIDENT

Location:	Sixty miles South of Nantucket, MA
Date:	October 31, 1999
Time:	0150 Eastern Standard Time (EST)
Flight:	EgyptAir Flight 990
Aircraft:	Boeing 767-366ER, Registration SU-GAP
NTSB#:	DCA00MA006

B. GROUP

Chairman: John O'Callaghan
Senior Aerospace Engineer
NTSB

Members: Mohamed A. Hamid Hamdy
Engineer - General Manager Training
EgyptAir

Maher Ismaiel Mohamed
Head of Airworthiness - Central Administration
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Lead Engineer - Aerodynamics, Stability & Control
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C. SUMMARY

The Aircraft Performance Group Chairman's Aircraft Performance Study for the EgyptAir flight 990 accident describes the results of using the various data sources to define, as far as possible, the motion of EgyptAir Flight 990. The study introduces the aircraft motion data collected during the investigation, describes the methods used to extract additional aircraft motion information from Digital Flight Data Recorder (DFDR), radar, Cockpit Voice Recorder (CVR), and weather data, and presents the results of these calculations.

The DFDR data presented in the Performance Study indicates a split, or asymmetry, in the left and right elevator panels about 27 seconds after the initial movement of the elevators in the nose down direction that initiated the departure from cruise flight. This Addendum to the Performance Study examines whether or not the recorded elevator split could have been caused by differential hinge moments on the left and right elevator panels. The results of these calculations indicate that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the DFDR.

This Addendum also presents the elevator deflection, throughout the flight profile described by the EgyptAir DFDR, that would result from a full nose-down elevator command under four different elevator control system conditions. These conditions are: (a) All three hydraulic systems operating; (b) Two of the hydraulic systems operating; (c) One of the hydraulic systems operating; and (d) All three hydraulic systems operating, but in a dual Power Control Actuator (PCA) valve jam scenario in which two of the PCAs are working to drive the elevator to its nose-down limit, but the third is working to keep it at neutral. For all of these conditions, the varying hinge moment on the elevators resulting from the changes in Mach number and angle of attack during the flight profile are accounted for. The results of the calculations are presented as plots of elevator deflection as a function of the Nantucket ASR-9 clock time presented in the Performance Study.

D. DETAILS OF THE INVESTIGATION

I. Hinge Moments Required to Produce Elevator Split

This section addresses the question of whether or not the elevator split recorded on the EgyptAir 990 DFDR could have been caused by aerodynamic forces on the tail surfaces.
The flight condition chosen for this study is as follows:

Radar Time:	01:50:30 EST
Altitude:	18,800 ft.
Mach Number:	0.96
True Airspeed:	600 kts.
Dynamic Pressure:	670 lb/ft^2
Left Elevator:	4° Trailing Edge Up (TEU)
Right Elevator:	3° Trailing Edge Down (TED)

To evaluate the aerodynamic loads on the tail surfaces required to result in the split, an assumption must be made about where the airplane's control system is attempting to position the elevators. At the flight condition under consideration, the elevator positions are split almost an equal amount about the faired elevator position, in opposite directions. These calculations therefore assume that the control system is attempting to command a 0° or faired elevator position.

With this assumption, the airloads on the right elevator must drive the elevator in the trailing edge down direction against the hydraulics, and those on the left elevator must drive the surface in the trailing edge up direction against the hydraulics. The airloads that tend to rotate the elevators about their hinges are expressed in terms of the elevator hinge moment coefficients, defined as

$$C_H = \text{Hinge Moment}/(q*S*c) \quad [1]$$

where q = dynamic pressure, S = elevator reference area, and c = elevator chord. Documents provided by Boeing describe the C_H as a function of tail angle of attack, elevator deflection, Mach number, and flap setting. The tail angle of attack (α_H) is a function of the airplane body angle of attack, the downwash angle at the tail, and the horizontal stabilizer deflection. The Boeing documents also indicate the amount of hinge moment that can be balanced by the forces provided by the hydraulic actuators. In the problem under consideration, the elevator deflection, Mach number, dynamic pressure, and flap setting are defined by the flight condition. If there is asymmetric flow around the left and right elevators, then the α_H of the left and right elevators may be different, resulting in differential hinge moments and differing surface positions. The table below lists the angles of attack required on the left and right horizontal tail surfaces in order to overcome both the hydraulic actuators and the elevators' own tendency to return to a faired position, and drive the elevators to the split positions recorded by the DFDR at 01:50:30.

# of Hydraulic Systems Operating	α_H on left tail required to drive elevator 4° TEU	α_H on right tail required to drive elevator 3° TED	Angle of attack difference, left - right
0	10.3°	-5.5°	15.8°
1	18.2°	-11.5°	29.7°
2	26.2°	-17.5°	43.7°
3	34.2°	-23.5°	57.7°

Linearized equations at Mach 0.91 (the highest Mach number for which 767 C_H data is available) were used to derive the numbers shown in the table. These work well for small elevator deflections (+/-5°) and angles of attack. However, the equations break down at larger angles of attack, because they do not account for tail stall, and can give tail angles of attack well above the stall. According to Boeing data, at low speed the tail will stall (reach its maximum lift coefficient) at angles of attack of about +/- 21°. At high speed, the stall angles are probably somewhat smaller, though wind tunnel data does not exist for these conditions.

The table indicates that with hydraulic power equivalent to 2 or more hydraulic systems operating, there is no angle of attack below tail stall that will move the elevators to their split positions. Data provided by Boeing indicates that during the period for which DFDR data exists, the hydraulic pressure available to the elevator PCAs to move the elevator surfaces would have remained at normal operating levels during the time between when the engines were shut down and the DFDR ended.

Considering the cases for which the elevator split can be obtained with tail angles of attack below stall (corresponding to 0 and 1 hydraulic systems operating), note that a considerable angle of attack difference between the left and right horizontal tails is required. It is difficult to conceive of a flight condition that can generate such asymmetric flow about the left and right horizontals, but two possibilities are (1) a roll rate, and (2) a sideslip angle.

The half-span of the tail is approximately 30 ft. At 600 kts., to generate an 5° angle of attack change at the tip of one horizontal (i.e., a 10° difference between left and right horizontal tips) requires a roll rate of 170 degrees/second. At the flight condition in question the roll rate is approximately 2 degrees/second.

The dihedral angle of the tail is 7°. This angle will cause one horizontal to be at a different angle of attack than the other while in a sideslip. However, to change the tail angle of attack by 5° (difference of 10° between the tails) requires a sideslip angle of 35°. Such a sideslip angle is inconsistent with the lateral load factor, aileron angles, and rudder angles recorded on the DFDR, and at the flight condition in question is probably beyond the aerodynamic and structural capability of the airplane.

These calculations indicate that with little loss of hydraulic power, there is no angle of attack on the tails below the tail stall which can generate the elevator split recorded on the EgyptAir DFDR. Furthermore, even at reduced hydraulic power where angles of attack below tail stall can cause the split, the roll rates and sideslip angles required to generate the necessary asymmetric angles of attack on the left and right horizontal tails are inconsistent with the performance capabilities of the airplane and with the data recorded on the DFDR.

II. Elevator Blowdown Angles

The accident airplane departs cruise flight and enters a dive in response to the nose down elevator movements recorded on the DFDR. The Systems Group considered several failures in the elevator control system that could result in uncommanded nose down movement of the elevator surfaces (see the Systems Group Chairman's Factual Report for a discussion of these failures). One of the failures considered by the Systems Group involves the failure of two of the three elevator PCAs on one elevator surface, such that these PCAs act to move the elevator surface in the nose down direction, while the remaining PCA acts to keep the surface at its faired position. There are several different mechanisms for achieving this failure (see the Systems Group Factual Report for the details), but in each case the position of the failed surface results from the equilibrium between the two failed PCAs, the unfailed PCA, and the aerodynamic hinge moments. This section presents estimates of the position of the failed elevator surface throughout the dive recorded on the DFDR under a dual elevator PCA failure scenario.

When the elevator control system commands full nose down elevator, the amount of elevator deflection actually obtained (the "blowdown" position) is limited by the aerodynamic forces working to restore the elevator to its no load, or zero hinge moment, condition. The resulting elevator deflection is that which balances the aerodynamic hinge moment against the moment produced by the elevator PCAs. The hinge moment coefficient that can be balanced by the PCAs is given by

$$C_H = \frac{P_L A_P n l}{qSc} \qquad [2]$$

where P_L = PCA load pressure, A_P = PCA piston area, n = number of hydraulic systems operating, and l = PCA actuator moment arm. C_H is nondimensional; the dimensional hinge moment is given by Equation [1] in Section I.

The PCA load pressure P_L is nominally 2,950 psi, and so with three hydraulic systems operating (n = 3) the numerator of Equation [2] becomes (2,950)A_P(3)l. In the dual PCA failure scenario, two PCAs are acting to move the elevator nose down, while the third is acting to keep it at neutral. However, in this scenario, n in Equation [2] is not simply (2) - (1) = 1 as one might expect, because the unfailed PCA uses more hydraulic pressure to keep the surface at neutral than each failed PCA uses to deflect the surface nose down. As the unfailed PCA is overpowered by the failed PCAs, its power piston is backdriven by the elevator surface, and the hydraulic fluid that would normally drive the piston is driven out through a pressure relief valve. This valve is set to 3,600 psi, so the unfailed PCA is essentially acting to keep the elevator at neutral with 3,600 psi pressure, while the failed PCAs are acting to drive the surface nose down with 2,950 psi pressure each. The resultant pressure moves the elevator surface down at (2)(2,950) - 3,600 = 2,300 psi. To determine the amount of hinge moment that can be balanced by this pressure, we can set P_L = 2,300 psi and n = 1 in Equation [2], or equivalently, keep P_L at 2,950 psi and set n = 2,300/2,950 = 0.78. This latter approach is used in the results shown below. The elevator blowdown curves are shown for four cases: three hydraulic systems operating normally (n=3); two systems operating normally and one system off (n=2); one system operating normally and two systems off (n=1); and the dual PCA failure scenario (n=0.78).

Equation [2] gives the hinge moment coefficient C_H that can be balanced by the elevator PCAs for various values of n. The elevator surface position that corresponds to this C_H is a function of Mach number (M) and angle of attack at the tail (α_H).

The best estimate of C_H is contained in the aerodynamic models of the Boeing 767-300ER engineering simulator. The simulator data is based on wind tunnel tests and updated with flight test data, where available. However, at high speed (flaps up), the simulator models C_H based solely on elevator deflection (δ_e), M, and stabilizer angle in “pilot units” (δ_{sPU}). While α_H is affected by δ_{sPU}, the simulator model of C_H at high speed does not include α_H explicitly (the low speed (flaps down) simulator model of C_H does include α_H explicitly). In order to account for the effect of changing airplane body angle of attack on the C_H and δ_e blowdown angles during the dive, an estimate of the effect of α_H on C_H at high speed must be obtained from the existing simulator models. The method used here to estimate this effect is described below.

The maximum Mach number contained in the simulator data is 0.91, corresponding to the dive speed limit of the airplane. During the accident, the maximum M attained during the time the DFDR was operating was 0.99. To estimate the C_H at Mach numbers above 0.91, Boeing extrapolated the 767 elevator hinge moment data to Mach 0.98 based on 777 wind tunnel data available at Mach numbers .91, .94, and .96. The 777 and 767 have aerodynamically similar horizontal tails and elevators. The extrapolated data describes C_H in a three dimensional table with δ_e, M, and δ_{sPU} as independent variables.

Because the simulator C_H data is dependent on δ_{sPU} and not α_H, the effect of changing the freestream body angle of attack (and also α_H) will not be reflected in the solution for δ_e using the data directly. To approximate the effect of changing α_H, we observe that:

$$\alpha_H = \alpha_B - \varepsilon + \delta_s \qquad [3]$$

where α_B is the body angle of attack, and ε is the downwash angle at the tail. ε is assumed to be approximately equal to the downwash angle at the wing:

$$\varepsilon \approx \frac{C_L}{\pi A R e} \qquad [4]$$

C_L is the lift coefficient, AR is the airplane aspect ratio, and e is a wing efficiency factor, assumed to be about 0.8.

The δ_s in Equation [3] is the angle the horizontal stabilizer chord makes with the fuselage reference angle, with positive angles in the leading edge up direction. This measure of stabilizer angle is different than the stabilizer angle recorded by the DFDR, which is in pilot units (δ_{sPU}). The relationship between δ_s and δ_{sPU} is

$$\delta_s = 2° - \delta_{sPU} \qquad [5]$$

The C_H tables contain data for δ_{sPU} angles of 0° and 6°, corresponding to δ_s angles of 2° and -4°, respectively. The α_B associated with the table data corresponds to cruise flight conditions. If the δ_{sPU} angles in the tables could be replaced with equivalent α_H angles at cruise conditions, then the tables would describe the C_H as a function of α_H and could be used to estimate the effect of the changing α_B on the C_H throughout the dive.

From the DFDR data, while cruising at 33,000 feet, α_B = 3°, $\varepsilon \approx$ 1.5°, and δ_{sPU} = 3.2°. Using Equation [5] gives δ_s = -1.2°, and then α_H = 0.3° follows from Equation [3][1]. So at this condition, an α_H of 0.3° corresponds to a δ_s of -1.2°. If we hold α_B and ε constant, then a change in δ_s is equivalent to a change in α_H , and a δ_s of 2° would correspond to an α_H of 0.3° + {2° - (-1.2°)} = 3.5°. A δ_s of -4° would correspond to an α_H of 0.3° + {-4° - (-1.2°)} = -2.5°. By changing the C_H tables to be dependent on α_H instead of δ_{sPU}, and by associating the data corresponding to δ_{sPU} = 0° with α_H = 3.5° and the data corresponding to δ_{sPU} = 6° with α_H = -2.5°, the C_H can be determined as a function of δ_e , M, and α_H.

[1] The purpose of the downwash approximation given by Equation [4] is to provide a simple method for recognizing the effect of downwash on α_H. A calculation of the actual downwash would require table lookups of flight updated simulator data. The simple method used here provides a mechanism for accounting for the effect of α_H on C_H throughout the dive. However, it should be noted that the actual downwash at the cruise condition is 4.2°, not 1.5°, resulting in an α_H of -2.4°, not 0.3°, as calculated here. These differences can shift the blowdown angles up or down slightly, but do not have a significant effect on the shape of the curves.

To calculate the blowdown angle, the C_H that can be balanced by the PCAs is calculated using Equation [2]. At each point during the dive, M is known, and α_H can be calculated using Equations [3] and [4]. An initial estimate of δ_e is made and the corresponding C_H is determined from a three dimensional table lookup of the modified simulator tables using the δ_e estimate, M, and α_H as independent variables. This C_H is compared with the C_H from Equation [2], and if they do not match, the δ_e estimate is adjusted until they do. The resulting δ_e is the blowdown angle.

The solutions for δ_e with n = 0.78, 1, 2, and 3 are shown in Figure 1. These solutions are the blowdown angles corresponding to the Dual PCA Failure and various hydraulic systems turned off. The elevator positions recorded on the DFDR are also shown in Figure 1. The elevator blowdown angle is primarily dependent on the dynamic pressure, decreasing as dynamic pressure increases. Changes in angle of attack produce oscillations about the general trend set by the increasing dynamic pressure. Nonlinear Mach effects become more pronounced after about 01:50:07, where the Mach number is increasing through 0.86 and the slope of the blowdown curves increases abruptly. The extrapolated C_H data provided by Boeing indicates that the C_H for a given δ_e deflection starts to increase significantly above Mach 0.86, and at Mach 0.98 reaches over twice its Mach 0.8 value for some values of δ_e and α_H .

E. CONCLUSIONS

This Addendum to the Airplane Performance Study for the EgyptAir Flight 990 accident indicates that it is unlikely that the split between the left and right elevator surfaces recorded by the DFDR could have been produced by asymmetric aerodynamic forces acting on the elevator surfaces.

The Addendum also presents the elevator blowdown angles corresponding to different numbers of hydraulic systems powered on and off, and to a Dual Elevator PCA Failure scenario. The blowdown angles are estimated using extrapolated, non-linear elevator hinge moment data. The results of the calculations are shown in Figure 1.

[redacted]

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April 19, 2000

EgyptAir 990 Elevator Blowdown Angles

With Nonlinear Mach, Elevator Angle, and α_H Effects

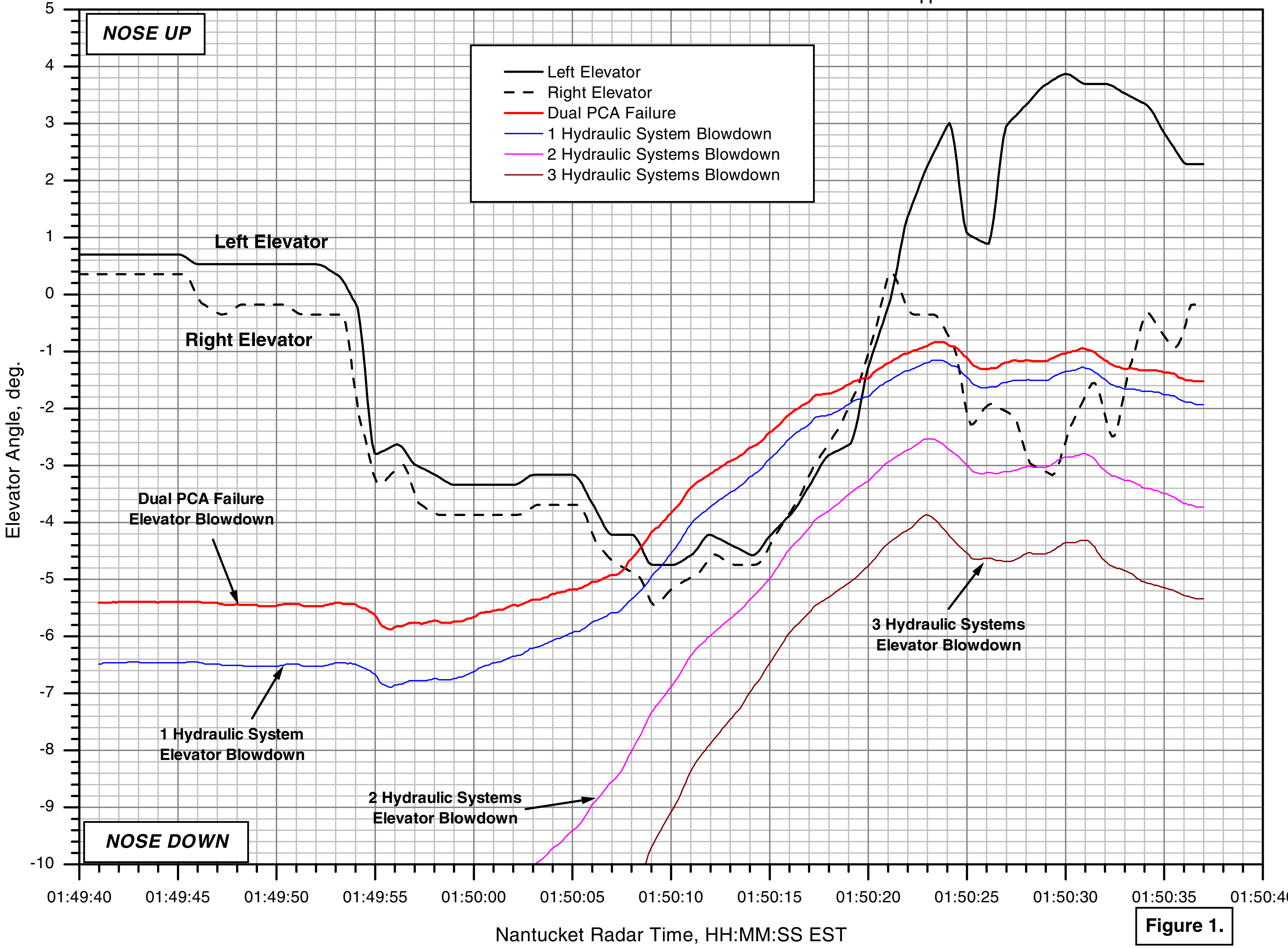

Figure 1.