

January 12, 2001

Mr. Gregory Phillips  
National Transportation Safety Board  
490 L'Enfant Plaza East, S.W.  
Washington, D.C. 20594

Dear Mr. Phillips:

The Egyptian Civil Aviation Authority requests and authorizes you to place the Response of EgyptAir to October 31, 2000 Submission of The Boeing Company regarding the EgyptAir Flight 990 investigation into the public docket for the EgyptAir Flight 990 investigation.

Sincerely,

A black rectangular redaction box covers the signature of the sender.

Captain Mohsen El Missiry  
Chief of Egyptian Investigation Committee

Response of EgyptAir  
to  
October 31, 2000 Submission of  
The Boeing Company  
Regarding  
The EgyptAir Flight 990 Investigation

## SUMMARY

On October 31, 2000, the Boeing Company presented a "Submission to the National Transportation Safety Board for the Egyptair 990 Investigation" in which Boeing advised that it "does not believe that the loss of Egyptair 990 was the result of a mechanical failure of the aircraft or aircraft systems."<sup>1</sup> Although Boeing, as the aircraft manufacturer, emphasized its expertise, sophistication, and "approximately 13,000 recorded man-hours" devoted to the investigation, a close reading of Boeing's analysis demonstrates that it is based upon a selective view of the evidence and contains sufficient omissions and inaccuracies to make it unreliable. Because there is a danger of too-ready an acceptance of what purports to be scientific analysis coming from Boeing, EgyptAir, as the carrier operating the 767 involved in the accident, believes that the NTSB must carefully examine the methodology and assumptions on which Boeing's conclusions rest. As EgyptAir demonstrates in these comments to Boeing's submission, an objective review of the evidence, while possibly not conclusive proof of a mechanical cause for this accident, is, nevertheless, sufficient to support a mechanical defect as a plausible theory and to warrant the rejection of Boeing's conclusory view. Indeed, when considered objectively, the evidence suggests that the accident aircraft was defective prior to its departure from New York on October 31, 1999 and thereafter lost the right elevator and left engine before crashing into the Atlantic Ocean.

In particular, Boeing fails either to account for or to comment upon the following:

1. On August 25, 2000, the Federal Aviation Administration ("FAA") issued Airworthiness Directive ("AD") 2000-17-05 concerning reported failures of the bellcrank shear rivets in the elevator system of the 767. The FAA demanded the expedited inspection of these

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<sup>1</sup> A copy of Boeing's submission is attached as Appendix A.

parts, describing the potential for multiple failure as “catastrophic.” Although there are numerous documented instances of sheared or partially sheared rivets, Boeing has yet to explain how or why this damage is occurring to a critical component of the elevator system.

2. Even though it cannot yet be determined whether the sheared bellcrank rivets are either the cause or the effect of a mechanical problem related to the accident, the information from the Flight Data Recorder (“FDR”) is remarkably consistent with test data of a jam of two right elevator servos in the trailing edge down (“TED”) position. The differences between the test data and the FDR can be adequately explained as either performance variances within normal limits or the limitations of the test facilities and protocols. In addition, because the FDR does not record control column positions, it is impossible to determine whether or not the observed variances are attributable to mechanical, human, or aerodynamic causes.

3. In addition to sheared bellcrank rivets, the examination of the flight 990 wreckage also revealed substantial internal damage to the right outboard elevator power control actuator (“PCA”). Of the four PCAs recovered, this was the only one damaged internally. The most obvious damage was that the pin securing the spring guide was sheared and that the spring itself was looped over the guide. Because impact damage would likely have caused related witness marks, the absence of such impact witness marks suggest that the observed damage occurred prior to impact with the water.

4. The elevator split recorded during the last 15 seconds of FDR data would -- if it occurred as recorded -- have resulted in a rolling moment requiring aileron deflection of approximately 26 degrees to achieve the recorded FDR roll angles. The absence of the calculated roll and the associated aileron deflection raises the question of whether the right elevator surface was still attached to the airplane during the recorded split. Analysis shows that

the recorded roll and pitch during the last 15 seconds of data is much closer to the expected aircraft performance if the right elevator is missing.

A. The Flight Data Recorder Shows Evidence of a Mechanical Malfunction

Although the most heavily scrutinized FDR data is for the last 60 seconds of flight 990, the FDR contains 25 hours of data detailing the aircraft's performance prior to the accident. In particular, this data shows an unusual pattern of 11 autopilot disconnects, none of which Boeing analyzed in detail. Specifically, during the flight a day earlier from New York to Los Angeles, the Captain disconnected the autopilot of the flight 990 aircraft three times between 10,000 feet and approximately 7,000 feet as the airplane was descending for landing at the Los Angeles airport.

Capt. Gamal Arram, who was in charge of that flight, reported that he observed an unusual movement in the control column and disengaged the autopilot to determine whether there was a malfunction. When he was unable to reengage the autopilot, Capt. Arram took the unusual step of hand flying the aircraft for the remainder of the flight. Capt. Arram reported that the autopilot once again functioned normally after the aircraft landed and continued to operate properly when it was checked by the a maintenance crew in Los Angeles.

The erratic behavior of the autopilot caused Egyptian investigators to review all instances of autopilot disconnection on the 25 hour FDR recording. Of special note is that each time the autopilot was disengaged, there was an obvious downward movement of elevators, with the right elevator showing a greater deflection than the left. To analyze this data, EgyptAir test flew another 767 and performed a series of autopilot disconnects and reviewed the FDR data from those test events.

This set of test autopilot disconnects was performed during cruise on a flight from Cairo to Rome. As was expected, the data relating to these disconnects showed no marked difference between autopilot and manual operation at the moment the autopilot disconnected. See Figure 1. This is in contrast to the data for the flight 990 aircraft where there was a consistent downward deflection when the autopilot was disengaged. This analysis shows that an anomaly existed in the Flight 990 elevator system even before the aircraft left New York for Cairo on October 31, 1999 -- a latent defect that could not be detected by the crew.

In light of these facts, it is plausible to believe that -- just as Capt. Arram had done a day earlier -- the First Officer on flight 990 disconnected the autopilot after observing some unusual movement in the control column. It should be recalled that during the backdrive of the Boeing simulator, the investigators observed an unexpected movement of the control column just prior to the autopilot disconnect. Once the autopilot was disconnected, the latent defect manifested itself by an obvious change in the elevator position. As shown in Figure 2, the left elevator deflected TED approximately 0.2 degrees and the right elevator deflected TED approximately 0.6 degrees. These deflections were accompanied by a decrease in the vertical load factor of about 0.07 "g." At the same time, the pitch attitude began to decrease see Figure 3 (elapsed time at the x-axis is selected to be 0 at time 1:50:00 ET). The correlation of elevator movement with vertical load factor and pitch change confirms that the recorded elevator deflection did actually occur. This deflection of the elevators with the right elevator leading is what one would expect if one power control actuator ("PCA") had jammed.

Figures 4, 5, and 6, which are extracted from the ground test data, indicate the elevator movement at a no-load condition as a result of a single PCA valve jam in the TED direction.<sup>2</sup> These figures show the results of three separate tests under the same test conditions –single PCA jam, 770 psi feel pressure, and pilot column sweep. They indicate that the right elevator is always leading the left elevator and are not consistent with the mathematical model included in Boeing report B-H200-17068-ASI-R2 -Split Elevator Failure Scenario, dated September 29, 2000 and Boeing report B-H200-17026-ASI, -767 Elevator System Operation with Regard to Column Splits, Aft Quadrant Splits, and Column Jams, dated August 2, 2000.

At FDR time of 1:49:54 (time= -6 seconds), both elevators deflected further TED with the right elevator leading. This is consistent with a second PCA jamming in the TED position (see Boeing report B-H200-17068-ASI-R2 -Split Elevator Failure Scenario, dated September 29, 2000).

As a result of the dual PCA valve jam in the trailing edge down direction, the elevator columns would be pushed forward, and would prevent stabilizer manual electric trim inputs and inputs from the Mach trim system.

The dive caused by the elevators' TED movements would result in increasing speed which would cause elevator deflection changes in the upward direction (starting at time = 10 seconds). This is consistent with the FDR elevator data (see Elevator Blowdown Curves, Flaps Up, One Hydraulic System Operating, Page 3-68, Boeing Document D613T161 Flight Control System Data for the 767 Training Simulator).

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<sup>2</sup> Unless otherwise indicated on the Figure, charts attached to these comments were derived from data sets reflecting the results of simulator and ground testing conducted at Boeing. Charts used by Boeing in its submission and in its prior letters and reports to the NTSB reflect only a single plot for each case.

At time 1:50:07 (time = 7 seconds, with associated audible warning), the airplane then exceeded 0.86 Mach, which is its maximum operating Mach number. Then, the airplane exceeded 0.91 Mach, which is the maximum design Mach number of the airplane, at time 1:50:13 (time = 13 seconds). The airplane reached a maximum speed of approximately 0.99 Mach during the dive (NTSB performance group chairman factual report, based on the FDR accelerometer data).

Figure 7 shows the expected elevator deflection as a result of a dual PCA control valve jam using the Boeing hinge moment data with and without considering the effect of airplane body angle variation and the FDR elevator data. These expected deflections were derived by the NTSB performance group chairman and validated by the Egyptian Delegation. From elapsed time of 7 seconds, the calculated right elevator position is within 1 degree of the FDR.<sup>3</sup>

B. Analysis of the Wreckage Indicates Damage to the Elevator System Prior to Impact

In its submission, Boeing asserts that its examination of the wreckage from flight 990 revealed no “failure condition” that could have “caused or contributed to the initial pitchover.” In this carefully worded conclusion, Boeing avoids any comment on the sheared bellcrank rivets that are the subject of the FAA’s AD and any comprehensive analysis of the damaged elevator components that were recovered.

As noted above, and as described in the NTSB metallurgical report, three right elevator bellcrank assemblies were recovered. Two sets of bellcrank rivets were sheared in one direction, one set in the opposite direction. This evidence alone indicates that they were not damaged by a single, simultaneous force such as would arise on impact with the ocean. In addition, the right

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<sup>3</sup> Figure 7 is from the NTSB and does not account for any differences caused by the rate at which the failure occurred. In addition, the labels for right and left elevator are reversed.



outboard elevator PCA and servo were recovered. The manifold housing containing the servo valve was found attached to the PCA by the input arm. The bolts that connected the manifold housing to the PCA had been sheared. Examination of the servo revealed that the pin holding the spring guide to the slide had been sheared and the spring had looped over the spring guide. For the reasons described below, it appears that this damage occurred before the impact with the water.

Boeing reported on an analysis of the forces required to shear the spring guide pins in their reports B-H200-17066-ASI and B-H200-17082-ASI. There are several errors in the technical analysis, but the primary flaw is even more fundamental. First, the acceleration needed to shear the pins in the spring guide is based on a double shearing force of 300 pounds. Based on the mass of the spring guide, a load of 19,551 “g” is needed to shear the pin if only inertial forces are considered. This is in agreement with the Boeing analysis. Boeing calculates the acceleration needed to get the slide and guide up to 57.25 mph. This was done correctly, but this calculation only determines the acceleration needed to get to this speed, not the acceleration needed to create sufficient force to shear the pin. To fail the pins in the guide, the slide must be decelerated from 57.25 mph to zero speed at a rate of 19,551 “g.” To put this value in perspective, flight data recorders are designed to withstand 4000 “g” in an impact.

To achieve an acceleration on the spring guide, the combined slide/spring/spring guide unit must be decelerated. The pin will then be loaded in shear during the deceleration. Boeing reported the mass of the slide as 47.5 grams (0.105 lbm). The force required to stop the slide alone is 2053 lbf (= 19,551 g \* .105 lb). If the slide hit the end cap or the overtravel cam with this much force, a significant witness mark would have been produced. None was observed.

The Boeing analysis reported that the loading required to shear the manifold-to-actuator bolts was 1843 “g.” The maximum loading that was applied to the servo was less than 10% (1843/19,551) of the load required to fail the pins in the spring guide. Once these bolts are sheared, the servo is no longer restrained and will be at zero “g” until it hits something else.

The energy calculations that form the basis of the Boeing analysis are valid, but they only put a minimum value on the speed of the guide. Paraphrasing, the Boeing analysis states that if the speed of the airplane was less than 57 mph, there is not enough energy available to shear the pins in the spring guide. It does not state that, if the speed is greater than 57 mph, the pins will shear. That analysis requires the determination of forces applied at specific locations. The second Boeing report on the servo damage addresses forces, but it ignores how those forces could possibly be applied. Neither report addresses the principle of conservation of momentum, which relates mass, speed and time. To get the acceleration needed to fail the spring guide pin, the guide must be slowed from 57 mph to zero speed in approximately 0.000133 seconds, an impossibly small elapsed time considering the size and lack of structural rigidity of the airplane, the fact that it impacted water, and the relative lack of damage to the parts to which the PCA was attached.

Based on a corrected Boeing analysis, the internal damage to the right outboard PCA servo must have predated the accident. Because this failure is latent, this damage could have occurred anytime after the last “A” check.

With the spring looped over the spring guide and inhibiting the movement of the slide, the slide may be jammed in an off-null position. Hydraulic fluid would then be ported to the PCA ram when the elevator control system would be asking for no flow. The remaining PCAs

would then compensate for this malfunction by porting fluid to the other side of the PCA thereby balancing the system and hiding the defect from the crew.

In its submission to the NTSB, Boeing implies that a jam did not occur by stating “[t]here was no evidence from the examination that the spring coil or spring guide had contacted adjacent components such that control valve jamming could result.”<sup>4</sup> (Page A-21). In the NTSB Material Laboratory Factual Report No. 00-071 in Figure 19, there are marks around the circumference of the sleeve of the servo that could be evidence of jamming. Even if the marks in the servo sleeve were not produced by a jam, it does not mean that no jam occurred. In any event, Boeing did not even address the existence of these marks in its submission. There may be no physical evidence of a jam; however, the spring and spring guide were found in an anomalous condition which could be evidence of a jam. More importantly, however, the extensive NTSB investigation of PCA jamming in connection with USAir 427 showed that a valve jam could occur without leaving any observable trace. Consequently, even the absence of physical evidence on which Boeing relies is not proof that no jam occurred.

In addition to the damage to the bellcrank rivets and the spring guide pin, the rams on the recovered PCAs were in different positions, also indicating damage to the elevator system prior to impact. The ram on the right outboard PCA was found fully retracted. This position corresponds to a full trailing edge down position of the elevator. There were three other PCAs recovered. Two of those PCAs had witness marks on the ram and/or the rams were bent showing how far each ram was extended at the time of impact. The third PCA was found with the ram partly extended but no witness marks were found on the ram.

<sup>4</sup> Boeing goes even further by suggesting that the NTSB Systems Group concluded that a dual PCA jam would not produce the elevator motion recorded on the FDR. This is simply not true. EgyptAir, a member of the Systems Group, has consistently asserted a contrary view, and the Group has never reached a consensus or published a factual report on this issue.

The right outboard PCA had no witness marks on the length of the ram. Further examination showed essentially no damage to the ram. From the inspection notes, "Upon removal, piston appears straight. Inside of bore and piston are much cleaner than prior units examined." The position of the ram when it was recovered and the lack of damage to the ram both indicate that the ram was fully retracted upon impact with the water.

The other three PCAs that were recovered were found with their rams partly extended. If one of these three PCAs was also driving the right elevator, there is an apparent conflict between the amount of ram extension on the right outboard PCA and the other one. Two PCAs connected to the same elevator cannot have a significantly different amount of ram extension if the elevator to which they are connected is intact. Since two PCAs on the same elevator had significantly different amounts of ram extension, that would suggest that the elevator lost its structural rigidity before impact with the water. It is most likely that the right outboard PCA was fully retracted when the airplane hit the water. A faulty servo valve could force that PCA to the fully retracted position, and the servo on the right outboard PCA was damaged as discussed in the previous section.

C. The Elevator "Split" May Be The Result of the Loss of the Right Elevator

At time 1:50:21 the FDR recorded a sudden and immediate change in the position of the right elevator from an essentially neutral position to over 3 degrees TED, while the left elevator continued to move approximately 4 degrees in the opposite, TEU, direction. Even though this data was recorded at about .99 Mach according to the NTSB's analysis -- a speed far in excess of the available data for the 767 -- and even though the FDR did not record the position of the cockpit control columns, the prevailing theory (with which EgyptAir disagrees) has been that the "split" was an indication of a struggle or dispute between the Captain and the First Officer.

Even a moment's objective evaluation demonstrates that such a conclusion cannot be supported. First, it must be remembered that the FDR elevator data only shows what is being recorded by the sensors and does not -- by itself -- indicate either the condition of the elevator system or the position of the control columns. Second, there is no indication of any struggle or dispute recorded on the CVR. Logic suggests that a struggle sufficient to produce such an aberrational elevator position would have corresponding verbal evidence. Here there is none. Third, for reasons yet to be explained, both Boeing and the NTSB have refused to consider the likelihood that uncommanded elevator positions resulted from unique aerodynamic phenomena produced as the aircraft approached the speed of sound.

It is undisputed that at the time the elevator split was recorded, the aircraft was traveling at .95 to .99 Mach and that the movement of the right and left ailerons was abnormal -- outboard ailerons that should have been locked in position were moving, and the right and left ailerons were moving in the same direction -- actions that cannot be commanded from the cockpit. Figure Assuming that the FDR data is accurate, it indicates either that extreme aerodynamic forces and shock waves were acting on the flight control surfaces or that there was some unidentified damage to the control system. Although the most likely explanation for the unusual aileron movement is aerodynamic forces created as the aircraft approached 1.0 Mach, there is no engineering or wind tunnel data available to make a reliable analysis.<sup>5</sup> More importantly, however, it is completely illogical to attribute the unusual aileron movement to aerodynamic

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<sup>5</sup> Boeing states that "... , the following functions are powered from the standby system to minimize crew work load following the complete loss of normal AC electrical power: L stabilizer trim and aileron lockout module(SAM)." This is not true. L SAM is powered from three power sources including Standby AC bus, Standby DC bus and left DC bus. Consequently, when main AC power is lost, left DC bus will also be lost, so stabilizer trimming from the captain side will not be possible.

forces and to reject summarily a similar explanation for the unusual elevator movement occurring at the same time.

As EgyptAir has pointed out previously, Boeing test data for the 767 is available only up to .91 Mach. All calculations of aircraft behavior after .91 Mach have, to date, been based upon an extrapolation of the known data. While the use of extrapolated data may be appropriate under certain circumstances, the use of such data to predict aircraft performance at transonic speeds may lead to erroneous conclusions. Because wind tunnel testing is necessary to obtain reliable data beyond .91 Mach and to show the magnitude of the error created by reliance upon extrapolated data alone, the only certainty is that conclusions based on data beyond .91 Mach are not reliable.

Although EgyptAir has urged both Boeing and the NTSB to obtain authoritative transonic data for the 767, both have declined to do so. Consequently, the only data available for analysis is extrapolated data. Using this information, which Boeing and the NTSB apparently believe is adequate, EgyptAir has determined that the FDR flight profile after the split is consistent with the expected aircraft performance only if the right elevator has departed the aircraft. As described below, this conclusion is based upon the absence of the expected rolling moment that would have been induced by a differential deflection of the elevators to the extent shown on the FDR.

Differential elevator deflection will induce a rolling moment. The first session of Boeing E-Cab simulations did not include this effect because the elevators were constrained to operate symmetrically. To address this shortcoming, the Egyptian Delegation conducted an approximate analysis of this effect. The analysis is approximate because detailed stability derivative information on the 767 is not available; therefore, the analysis was based on the sizes and

locations of the various components. Although the analysis is approximate, it shows that the rolling moment due to a differential elevator deflection is significant. Referring to the last 15 seconds of the FDR data, there is a question of whether the elevators were actually split, and the data raises the further possibility that the right elevator had departed the airplane by that time.

The Egyptian Delegation analysis consisted of two investigations that used control surface and aircraft state data from the Flight Data Recorder (FDR) for EgyptAir 990. The first investigation estimated the amount of aileron deflection needed to counter the rolling moment produced if there is a split in the left and right elevator deflection of the magnitude shown on the FDR. In the second analysis, a pitch simulation was performed to investigate the pitch attitude produced by the elevator deflections recorded by the FDR

If the elevators have a differential deflection as shown by the FDR data in Figure 9, they will produce unequal lift on the left and right sides of the tailplane resulting in an aircraft rolling moment. The methods of Roskam (Airplane Design, Part VI, Roskam Aviation and Engineering Corporation) were used to estimate the lift on the horizontal tail. Basic lift for the left and right tailplane was calculated using the angle of attack as recorded by the FDR in Figure 9. The elevator was treated as a plain flap and the incremental lift on the left and right surfaces was calculated. These lifting forces were then multiplied by a moment arm assumed to be acting at one-third the elevator half span. This resulted in a net rolling moment due to the differential deflection of the elevators. One time slice 1:50:28 ET( time = 28 seconds on the x-axis), was chosen to make these calculations. The relevant parameters are listed below:

$$\begin{aligned}
V_{cas} &= 456 \text{ kt} \\
M &= 0.93 \\
\delta_{e_L} &= -3.69 \text{ deg} \\
\delta_{e_R} &= 3.16 \text{ deg} \\
\alpha &= -9 \text{ deg} \\
\phi &= 4.4 \text{ deg}
\end{aligned}$$

The rolling moment coefficient for the inboard ailerons was then estimated. The outboard ailerons were assumed to be locked out at this high airspeed. Figure 9 demonstrates that the roll angle was small during this time period. The aircraft was well controlled in the roll axis; therefore, the rolling moment due to elevator would be balanced by the rolling moment from the ailerons. Equating the rolling moment due to differential elevator deflection with the restoring rolling moment due to ailerons, a differential aileron deflection was calculated. The result is

$$\delta_a = 26 \text{ deg}$$

However, if it is assumed, by this time step, that the right elevator is either gone or streamlined and producing no incremental lift, the aileron deflection needed to counteract the rolling moment due to the left elevator is

$$\delta_a = 4.4 \text{ deg}$$

FDR data for aileron deflection is shown in Figure 8. At this time step, the differential aileron deflection was 6.5 degrees, significantly smaller than the above 26 degrees predicted by the split elevator analysis but very close to 4.4 degrees predicted by the streamlined right elevator analysis.

This roll analysis suggests that an elevator split did not occur, but elevator deflection also controls pitch. Therefore, a longitudinal simulation of the aircraft motion after 1:49:53 (time = -



7 seconds) was performed. Models for lift, drag, and pitching moment were derived using the methods of Roskam. Inputs for elevator deflection and stabilizer incidence were taken from the FDR data. A full six-degree of freedom simulation was performed assuming that all lateral directional forces and moments were zero. The resulting pitch angle history is shown in Figure 10. With the elevator set as recorded on the FDR, the simulation continues to pitch down an additional 6 degrees beyond that recorded by the FDR. These results are due to the nose down pitching moment produced by the right elevator.

The results in Figure 11 are calculated assuming that the right tailplane was no longer producing a lift increment due to deflection of the right elevator. The maximum nose down pitch angle agrees very well with FDR data, and the simulated pitch begins to recover very closely in time to the FDR pitch attitude.

The effect of the pitching moment due to differential elevator deflection was also supported using data gathered during the second session of E-Cab simulations. During the second session, the programming of the simulator had been changed to allow differential elevator deflection. Plots extracted from the data recorded at the second E-Cab simulator session are shown in Figures 12 and 13. This example was recorded during a run in which the right elevator was deflected down approximately 5.5 degrees of right elevator deflection and the left elevator left to pilot control. Notice that differential aileron deflections of over 40 degrees are needed to keep the roll angle near zero. During the time of the alleged split elevator, the maximum differential aileron deflection recorded on the FDR was approximately 13 degrees (with the exception of one second at almost 20 degrees) and the average was about 6.5 degrees. These results can only be explained if the elevator did not actually produce the calculated rolling moment. Further, the positive load factor that was recorded on the FDR was due to the position

of the stabilizer with very little if any input from the elevator. Also, severe damage to the elevator would explain the inability to fully recover the airplane after the dive was stopped.

The results of the above analyses strongly suggest the possibility that some or all of the right elevator broke off some time shortly after the dive began. If that occurred, the information on right elevator position that was sent to the FDR is meaningless, and the argument that the recorded elevator split was due to a fight in the cockpit is simply wrong.

D. Boeing's Analysis of the Test Data Is Inconsistent, Incomplete and Selective

In its submission, Boeing states that it investigated various failures and could not find a failure condition that "matched the data recorded on the DFDR." In reaching this sweeping conclusion, Boeing nowhere explains, with respect to any parameter, what it would deem to be a "match," nor does it provide any detail as to how it concluded that there was no match. More importantly, Boeing fails to acknowledge fully either the limitations of the simulator and testing protocols or the existence of substantial test data, including ground test data on an actual 767. Any conclusions concerning the flight 990 accident should be based upon an analysis of all relevant data, not just data that Boeing – by unknown criteria -- deems "representative." Some of the reasons that Boeing's conclusion regarding the supposed absence of a match between the test data and the FDR must be questioned are discussed below.

1. The Engineering Simulator Did Not Provide an Accurate Model of Real Aircraft Performance

One of the primary sources for test data on which Boeing relies for the analysis in its submission is the engineering simulator ("E-Cab"). Although useful for certain purposes, the inherent limitations of the E-Cab make its data unreliable and potentially misleading in the context of the investigation of flight 990. The E-Cab was used to address aircraft performance

during several failure scenarios. Unfortunately, it did not perform like the airplane in several very important aspects:

- The E-Cab could not simulate the override mechanisms between the control columns.
- In the first session of E-Cab simulations, the elevators could only be operated symmetrically. In the second session of E-Cab simulations, differential elevator displacement was included in the software description of the system; however, the force feedback to the columns was not modeled.
- During the start of the dive, the left seat was vacant so all control input was provided by the right column. If the right column was pulled with sufficient force, the left and right sides of the elevator control system could have been disconnected at the override force values. Therefore, pulling on the right column would have a significantly altered effect on the operation of the left elevator. Under these circumstances, if the right elevator was being forced TED by two jammed PCAs, pulling on the right column would not have the same effect as pulling on the left column. This very important difference could not be simulated in the E-Cab; therefore, any conclusions on the potential recoverability of the airplane from the right seat alone are invalid.
- In the first set of simulations, the E-Cab assumed equal elevator deflection on both sides; however, the FDR data showed a slight difference in elevator deflection, then an elevator split condition at the end of the dive. This limitation had two important effects. First, if the right and left elevators were actually split during the accident, a significant rolling moment would have been produced. This rolling moment is controlled by aileron and/or rudder displacement. Neglecting this rolling moment

ignores a very important aspect of aircraft control and prevents a valid conclusion on the possibility of a recovery. Second, ignoring the possibility of a split elevator overstates the effectiveness of the elevator. By using one elevator position to represent the effect of one side deflected up and one side deflected down, the chosen position must be carefully selected to get the same pitching moment that was applied to the airplane. Finally, when the recoveries were attempted in the E-Cab after the FDR data had ended it was assumed that both elevators were available and were operating normally. This is clearly an incorrect simulation of the actual condition of the airplane and makes any conclusions arrived at using these results invalid.

- The E-Cab data produced an unrealistic relationship between control wheel force and wheel movement (see Figure 14) and showed the movement of the outboard ailerons at speeds beyond the lockout speed (see Figure 15).

More importantly, as a fixed-base simulator, the E-Cab could not duplicate the vertical load factors of between  $-0.1$  and  $+2.4$  experienced by the flight 990 crew during the accident sequence. Because the crew's ability to exert force on the flight controls would have been greatly diminished, and might even have been non-existent, under zero or negative "g" circumstances, the use of the E-Cab to evaluate crew responses was not appropriate and could be misleading.

These examples of the limitations of the E-Cab illustrate that this simulator and the data derived from the simulator do not accurately reflect the performance of an actual airplane or

what might have been expected of the flight 990 crew.<sup>6</sup> Therefore, any conclusions, such as those drawn by Boeing, must be carefully evaluated.

## 2. Boeing Often Ignored the More Reliable Ground Test Results

Because of the E-Cab limitations, Boeing also conducted ground tests using an actual 767 comparable to the EgyptAir 767. These tests often produced results that differed either from the E-Cab data or from results predicted by Boeing. For example, during the ground tests on a 767, it was found that a given column force results in a wide range of elevator deflections at the same specific condition and elevator feel pressure. Boeing used induced column force to determine elevator position; however, their ground tests showed that there is a band of elevator positions associated with any given force. In the analysis on which its submission is based, Boeing associated each value of column force with a unique elevator position, disregarding the test results showing that there is a band of possible elevator positions associated with a column force. See Figures 16-23. By ignoring the band of possible values of elevator position, Boeing reached conclusions that were not supported by their ground test data. (Compare with Boeing Figures 49, 50, 51, 52, 57, 59, 61, 62 attached in Appendix D of the Systems Group Chairman's Factual Report Addendum Regarding the Ground and Simulation Testing dated July 26, 2000).

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<sup>6</sup> In addition, Boeing made changes to the simulator that had no scientific basis and therefore contributed to erroneous data. For example, on page 3, Boeing states that, "Simulation modifications were made to lift, drag, and pitching moment parameters at speeds beyond the dive Mach number 0.91." These modifications were made with the intent of matching the FDR data with no experimental or theoretical basis and forced the simulation to match the FDR data. On page A-8, Boeing states that a "small artificial 'delta Cm trim' was introduced." There is no engineering basis for this correction. The only reason to use such an "artificial" variable is to force the output to a predetermined result. On page A-8, Boeing states that the column breakout forces and angles are different than those that were used in the March 2000 E-Cab simulations. The problem lies in the fact that the results of the March 2000 E-Cab simulations were used to form conclusions about the cause of the accident. This statement on page A-8 is confirmation that the E-Cab simulation did not accurately reflect the B-767; therefore, any conclusions reached based on the E-Cab simulations are invalid.

In another instance, ground tests were conducted on an exemplar B-767 to measure control forces and relate those forces to elevator deflection under various failure scenarios. As mentioned earlier, relating a force to an elevator deflection is imprecise at best. In addition, the test data revealed that when the column was not loaded by the pilot, there were non-zero column forces recorded. Boeing explained this discrepancy as due to temperature effects; however, Boeing neglected to record the temperature. In addition, no correlation between time of day or time since the last test could be established. Boeing arbitrarily chose to apply a different bias on each test in order to get zero force at the beginning of each test. This procedure is arbitrary and not based on any accepted scientific methodology.

Further, Boeing's explanation of force bias due to temperature effects is not supported by the data. Figure 24 shows the bias on the Captain's column force measurement increasing with time, with the suggestion that changes in temperature caused this change in bias. If temperature were the cause of the change in bias, the bias in the First Officer's force measurement would have increased as well, but it decreased. In addition, the bias on the First Officer's force measurement does not change in the nearly linear manner that the bias on the Captain's force measurement does. If both force transducers have the same specifications, they should react to temperature in a very similar manner; there should not be an opposite reaction to changes in temperature.

Figure 25 shows the bias during another test, but this time, the bias on the First Officer's force measurement increases much more rapidly than in the earlier test. This suggests that the temperature effects on the transducers are random because the temperature dependence more than triples between tests. Even if the temperatures had been recorded during the tests, that

information would not have been useful for calibrating the force measurement because of the apparently varying temperature coefficients.

The explanation that some of the bias is due to forces being applied prior to the start of the test is also flawed. If that were the case, there would be no logical way to apply a bias correction based on the value of the force at the start of the test. Each bias value depends on the amount of force being applied by the pilot at the precise time the test is started.

Even with the use of the Boeing methodology to correct the measured forces in the E-Cab, the forces induced as a result of PCA failures from the 767 ground test were significantly higher than the Boeing prediction for the induced force. However, most of Boeing's conclusions were based on their predictions and not on the actual forces as shown during the ground test.

In addition to ignoring the actual forces, in reaching its conclusions, Boeing only measured the forces applied to the control column by the Captain and the First Officer. Boeing failed to account for any induced force back driving the elevator control system as a result of the failure scenario being studied. Consequently, there is no accurate analysis of the actual control forces that the flight 990 crew faced.

### 3. Boeing's Selective Use of Test Data Resulted in Inconsistent Conclusions

In the studies leading up to its October 31, 2000 submission, Boeing also used information selectively or reached conclusions that were inconsistent with other Boeing data or predictions. For example, Boeing Report F-H200-17027-ASI of August 4, 2000 was written to address discrepancies between the results of the ground test and Boeing's calculated predictions. Starting on page 4 of the report, Boeing states that the stiffness of the elevator, the specific PCA that malfunctioned, and the location of the sensor all contribute to the elevator position recorded during the test and that the theory must be corrected in order to accurately reflect the ground test

results. Although Boeing's explanation is valid, Boeing did not use this approach when comparing the FDR data with a dual PCA failure. Instead, Boeing used the initial incomplete analysis (Boeing report B-H200-17068-ASI-R2 -Split Elevator Failure Scenario, dated September 29, 2000) to arrive at the conclusion that the FDR data was not consistent with a dual PCA failure. Boeing corrected its approach only to show that the ground test data was valid, but did not use that correction consistently. Boeing should have applied the correction in all cases where elevator position was predicted.

In another instance, Boeing's predicted dual PCA failure elevator differed significantly from its earlier submission to the NTSB on September 29, 2000, and also differed from the results obtained by the NTSB and the Egyptian Delegation as shown in Figure 7. The figure on page A-13 of the Boeing submission to the NTSB does not reflect the same data that were used by the NTSB as shown in Figure 7. The differences between the two representations of the data can lead to substantially different conclusions.

In Boeing's discussion titled "ELEVATOR BLOWDOWN" in Appendix A of its submission to the NTSB, Boeing shows calculated elevator positions. There are several inconsistencies with the data shown on page A-13. First, the plot of the calculated position does not match what Boeing submitted earlier. A comparison of the plot on page A-13 of the Boeing submission with the NTSB plot titled "EgyptAir 990 Elevator Blowdown Angles, Dual PCA Failure Scenario" with the NTSB performance group chairman plot (Figure 7) shows some significant, unexplained differences. Whereas the Boeing plot shows significant disagreement between the predicted elevator position and the information recorded on the FDR, the NTSB plot (which was independently verified by the Egyptian Delegation using data provided by Boeing) shows excellent agreement for a large portion of the time covered. The NTSB plot shows that



the recorded elevator position is substantially consistent with the test model of a dual PCA failure.<sup>7</sup>

In its report B-H200-17068-ASI-R2 (Split Elevator Failure Scenario, dated September 29, 2000), Boeing predicted that there would be no split in the normal deflection of the elevators if a single PCA jam had occurred, and it based some of its conclusions on this assumption. The ground testing of an exemplar 767 showed, however, that differential displacement of the elevators did occur. Figures 26 and 27 were derived from data collected by Boeing during the ground testing and shows that there is a difference in the deflections of the right and left elevators during a single jam failure, contrary to what was predicted by Boeing (difference is about 0.7 degrees). This elevator behavior is precisely what was recorded on the FDR after the autopilot was disconnected and before the dive began. Notice also that the Boeing analysis predicted that the induced force at zero displacement would be approximately 15 pounds. The testing showed that the measured force was between 30 and 45 pounds. This demonstrates the problem with using force as the independent variable in any analysis.

Finally, the data gathered during the ground tests conducted on the 767 does not support the Boeing study regarding single and dual PCA failures. In addition, the data does not correspond with the mathematical description of the elevator control system previously provided by Boeing. See Figures 28-31. These Figures present the elevators deflection as obtained from Boeing analytical model and the 767 ground test.

As shown in these figures, the “elevator force – deflection relationship” obtained from the 767 ground test is not consistent with the relationship obtained analytically in Boeing report B-H200-17068-ASI-R2 (Split Elevator Failure Scenario, dated September 29, 2000) and Boeing

<sup>7</sup> In fact, at a meeting in November 2000, Boeing representatives orally agreed that there was a substantial match with FDR data, but refused to put their observations in writing.

report B-H200-17026-ASI, (767 Elevator System Operation with Regard to Column Splits, Aft Quadrant Splits, and Column Jams, dated August 2, 2000). The actual ground test results always show much higher force at the same elevator deflection compared with Boeing analytical results on which Boeing based most of its conclusions.

Boeing's selective use of data, its use of simulator data that is contradicted by ground test data, its failure to measure control forces accurately, and its publication of inconsistent analyses combine to make the conclusions in its submission unreliable.

E. Boeing's Conclusions Regarding Crew Actions Are Erroneous

To support its conclusion that it could find no evidence of a "failure condition" that could have caused the accident, Boeing claims that the aircraft was recoverable under various failure scenarios induced during testing. In addition, Boeing imagines a series of emergency circumstances and concludes that the crew's actions were not "the expected pilot actions." Neither Boeing's recovery analysis nor its review of crew actions has any relevance to the determination of the cause of the accident. Ironically, Boeing's inability to find that the aircraft recovered and that the crew did not display predicted responses to emergency scenarios lends credibility to the view that flight 990 experienced a mechanical problem for which there was no training or checklist.

Boeing's assertion that all potential accident scenarios resulted in recovery of the aircraft by the pilots ignores the fact that those recoveries were achieved only in a simulator and without the exigencies of a real emergency, at night, over the ocean. Moreover, as noted previously, the simulator failed to model the performance of a real airplane in three critical respects:

- The simulator did not allow the column disconnect feature of a real 767.

- The simulator forces were not accurately imposed as shown by much higher column forces demonstrated in the ground tests.
- The simulator could not duplicate any “g” forces, much less the zero or negative “g” forces experienced by flight 990 – forces that were present precisely during the time that initiation of recovery efforts might be expected.

Consequently, any general assertion that all mechanical failure scenarios were recoverable is irrelevant and misleading.

Equally important, Boeing fails to describe what it deems to be a recovery of the aircraft. Certainly, one view would be that recovery means that the descent has been arrested, the pitch angle is zero, the wings are level, the heading is steady, and the aircraft is not rolling. Using that measure, it is readily apparent that the flight 990 crew did recover the aircraft prior to the end of the FDR recording. In its recovery analysis, Boeing omits any consideration of the possibility that the right elevator was missing and the fact that the left engine departed the aircraft during the climb from 16,000 feet to 24,000 feet. Presumably, simulator pilots faced with these additional problems would not have been able to “recover” the aircraft.

The last part of Boeing’s “analysis” consists of a review of various emergencies, along with a consideration of the crew’s actions. From the outset, it is obvious that Boeing’s purpose in including this material is not to advance the investigation into the cause of the accident or to address any safety issues, but instead to bolster the “blame the crew” theory by suggesting that the crew failed to respond appropriately to various events hypothesized by Boeing.

Boeing’s first example illustrates this point. Boeing contends that flight 990 lacked TCAS, but that even if there were an effort to avoid a collision, the “lack of control input [for 8 seconds after the autopilot was disconnected] is not consistent with what a pilot would do to

avoid another flying airplane (or object).”<sup>8</sup> Incredibly, Boeing failed to make even a minimal effort to obtain accurate information concerning the accident airplane. Flight 990 was, in fact, equipped with TCAS as it was required to be for transoceanic flight.<sup>2</sup> Moreover, it is neither correct nor realistic to assume that a pilot, who may well have disconnected the autopilot as a precautionary measure, would immediately initiate a radical avoidance maneuver. It is far more plausible that such a maneuver would occur only after the pilot concluded that the object was real and that avoidance was necessary. Certainly, such an evaluation could have consumed the 8 seconds noted by Boeing.

Boeing’s remaining analysis of emergency procedures is equally misleading with regard to the cause of this accident and requires little comment except for Boeing’s implication that the crew failed to take the proper steps to restart the engines. Boeing states that “there was not a successful attempt to regain an alternate source of electrical power because the DFDR stopped recording.” Although it is unlikely that Boeing really means – as it asserts – that the termination

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<sup>8</sup> Boeing’s attempt to link collision avoidance with a “rapid descent maneuver” is not justified. A rapid descent as described by Boeing is used primarily in connection with a sudden loss of cabin pressure or other emergency requiring prompt action to reach a lower altitude and is not intended as a procedure to avoid imminent collision which may require evasive action in the form of a turn or climb rather than a “rapid descent.”

<sup>2</sup> In other instances, Boeing also misstated the configuration of the accident airplane. On page B-5, Boeing states that “....., the following functions are powered from the standby system to minimize crew work load following the complete loss of normal AC electrical power: spoilers panels 1,5,6,7,8,12.” This is not true. These spoilers panels are controlled from spoiler control modules (M533, M534, M535). These modules are supplied from CSEU power supply module (M538, M539) which are powered from L & R AC bus and DC bus. On page B-5, Boeing states that “....., the following functions are powered from the standby system to minimize crew work load following the complete loss of normal AC electrical power: L stabilizer trim and aileron lockout modules(SAM).” This is not true. L SAM is powered from three power sources including Standby AC bus, Standby DC bus and left DC bus. Consequently, when main AC power is lost, left DC bus will also be lost, so stabilizer trimming from the captain side will not be possible.

of the DFDR prevented the acquisition of electrical power, it is interesting that Boeing fails to acknowledge that because APU parameters are not recorded by the FDR, it cannot be determined whether the crew engaged the APU control switch. Moreover, an APU start requires the APU to reach 95 percent RPM which itself takes approximately 45 seconds. The FDR ended before an APU start could have been completed. Further, Boeing ignores the fact that an engine restart cannot be accomplished until the aircraft speed drops within the engine restart envelope. The deployment of the speedbrakes by the flight 990 crew would have helped to reduce the speed of the aircraft and to bring it within the restart parameters set by Boeing and the engine manufacturer.

Boeing's selective use of information is calculated to give the misleading impression that the crew acted improperly. The fact is, Boeing's "analysis" of this area omits consideration of many facts, misstates others, and makes assumptions unsupported by any evidence. Boeing's factual errors and selective assumptions should not be accepted as illustrative of the accident scenarios.

## CONCLUSION

- Boeing's submission to the NTSB dated October 31, 2000, contains many inaccuracies, omissions and the selective use of evidence.
- Boeing's own ground test and simulator data does not support its conclusion that DFDR data is inconsistent with a dual jam scenario.
- A dual PCA control valve failure on the right elevator is consistent with the flight 990 FDR data.
- There is physical evidence consistent with a malfunction in the elevator control system which might be the plausible cause for the accident.

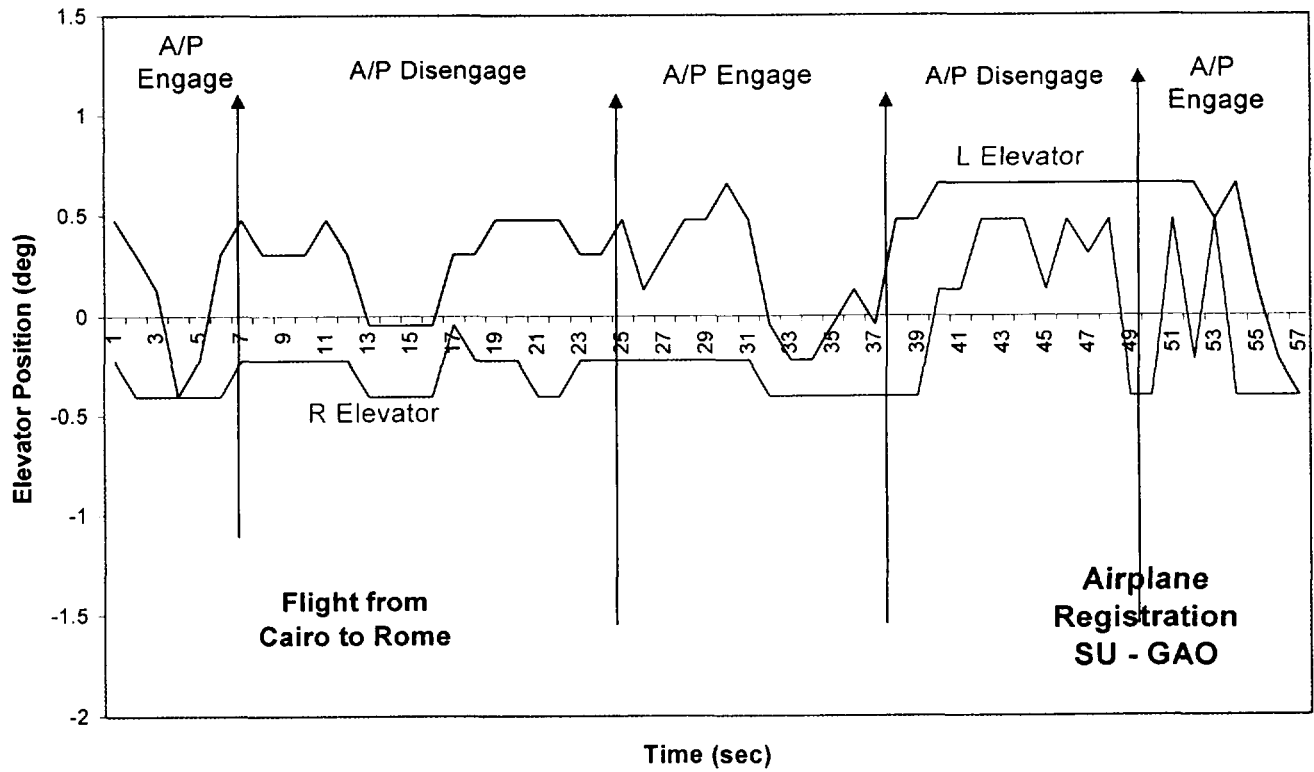


Figure 1. Elevator Response to Autopilot Disconnect on an Airworthy B-767



Figure 2. FDR Elevator Deflection



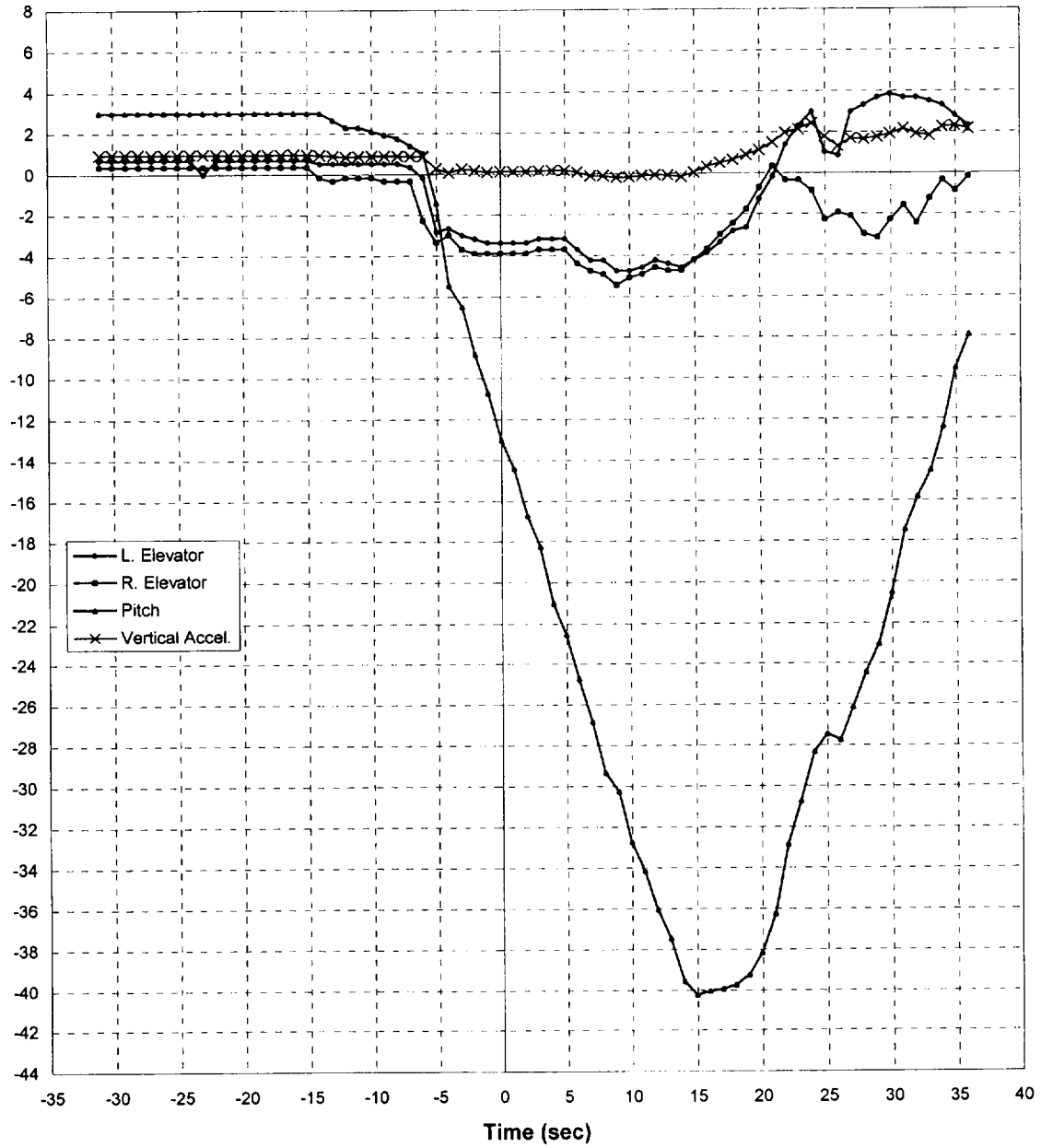


Figure 3. FDR Elevator Deflection, Pitch, and Vertical Acceleration

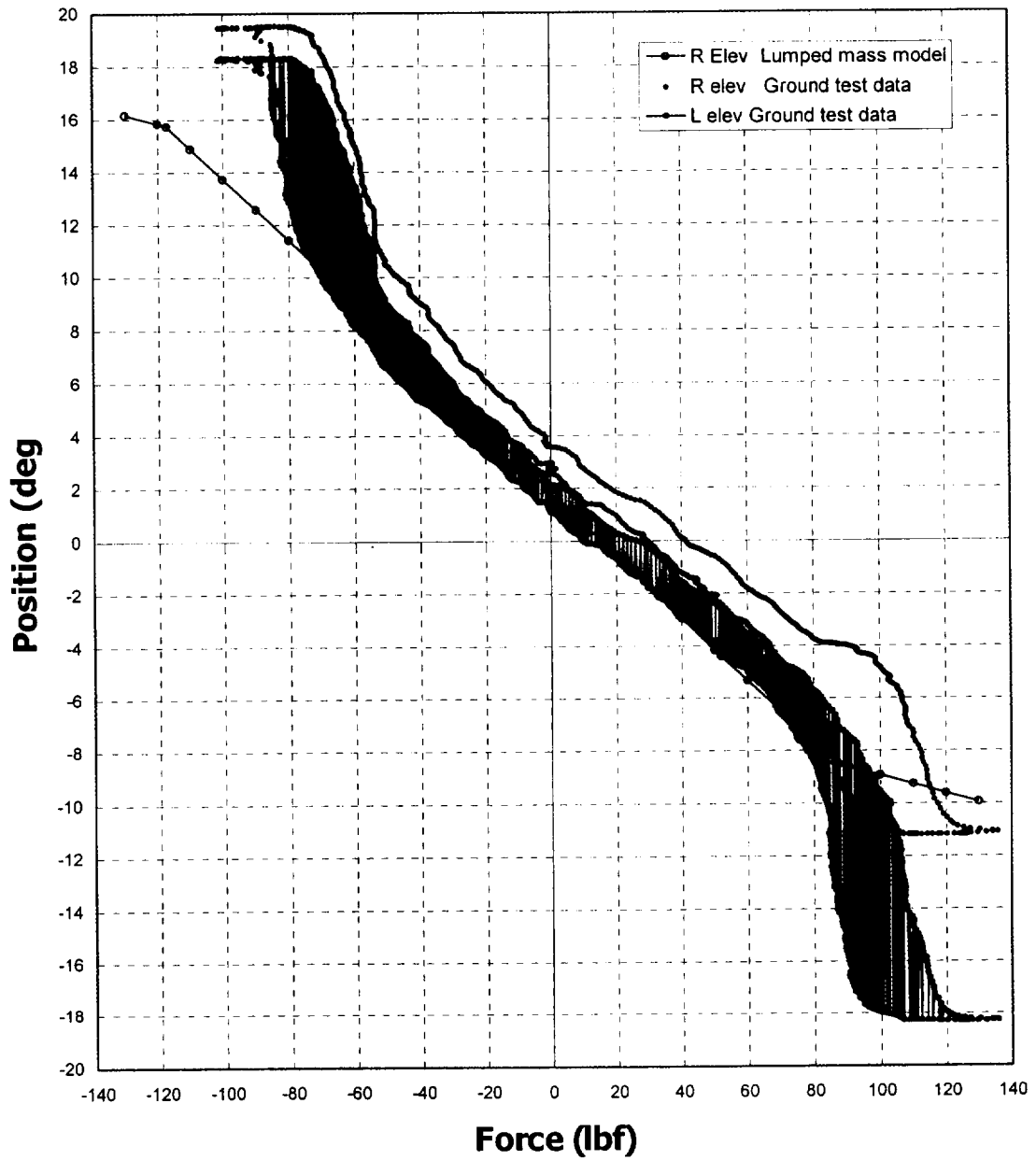


Figure 4. Elevator Deflection from Ground Test A and Analytical Model  
 Single PCA Control Valve Jam on the Right Elevator, 770 psi Feel Pressure, Pilot  
 Control Sweep

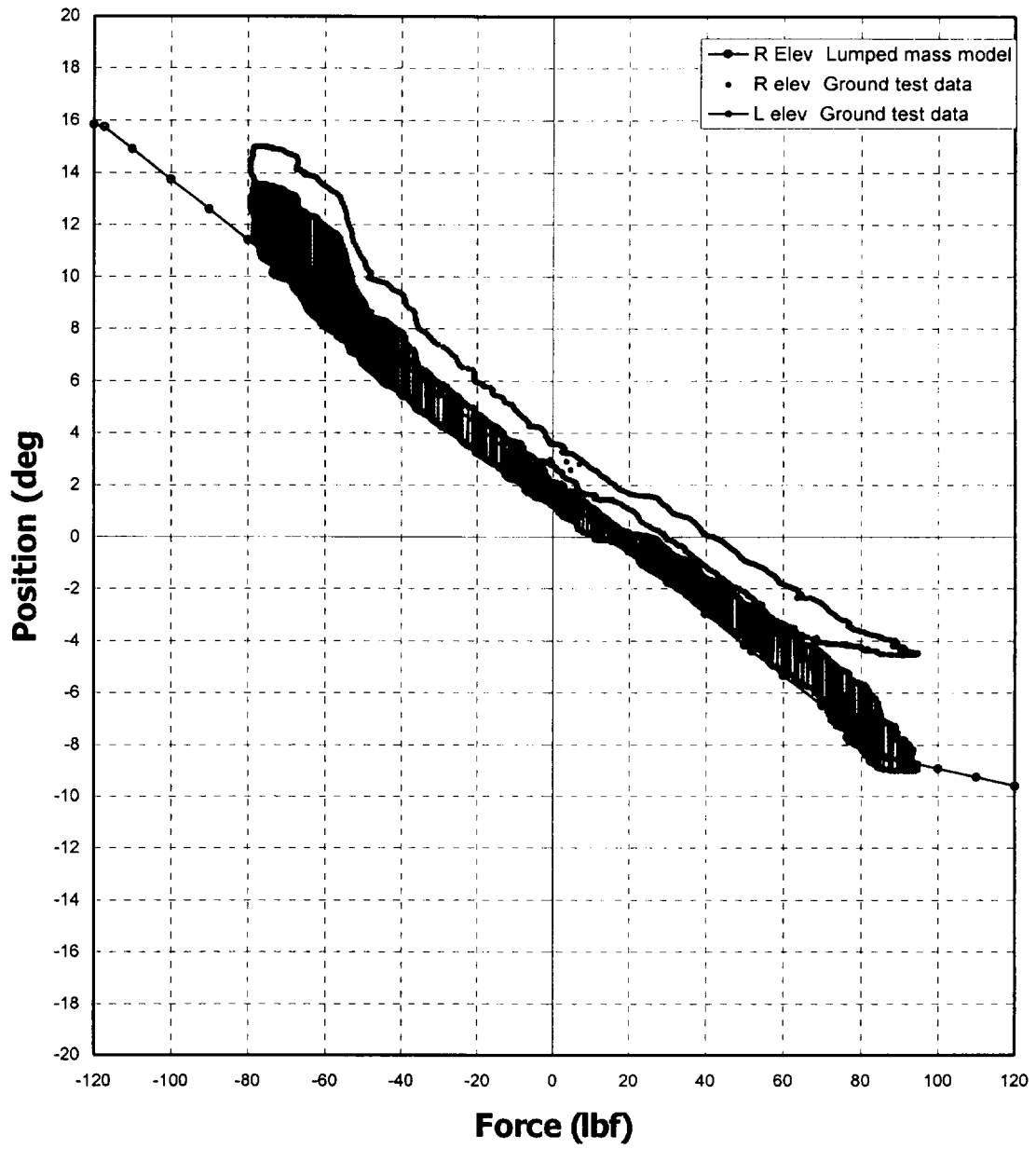


Figure 5. Elevator Deflection from Ground Test B and Analytical Model  
 Single PCA Control Valve Jam on the Right Elevator, 770 psi Feel Pressure, Pilot  
 Control Sweep

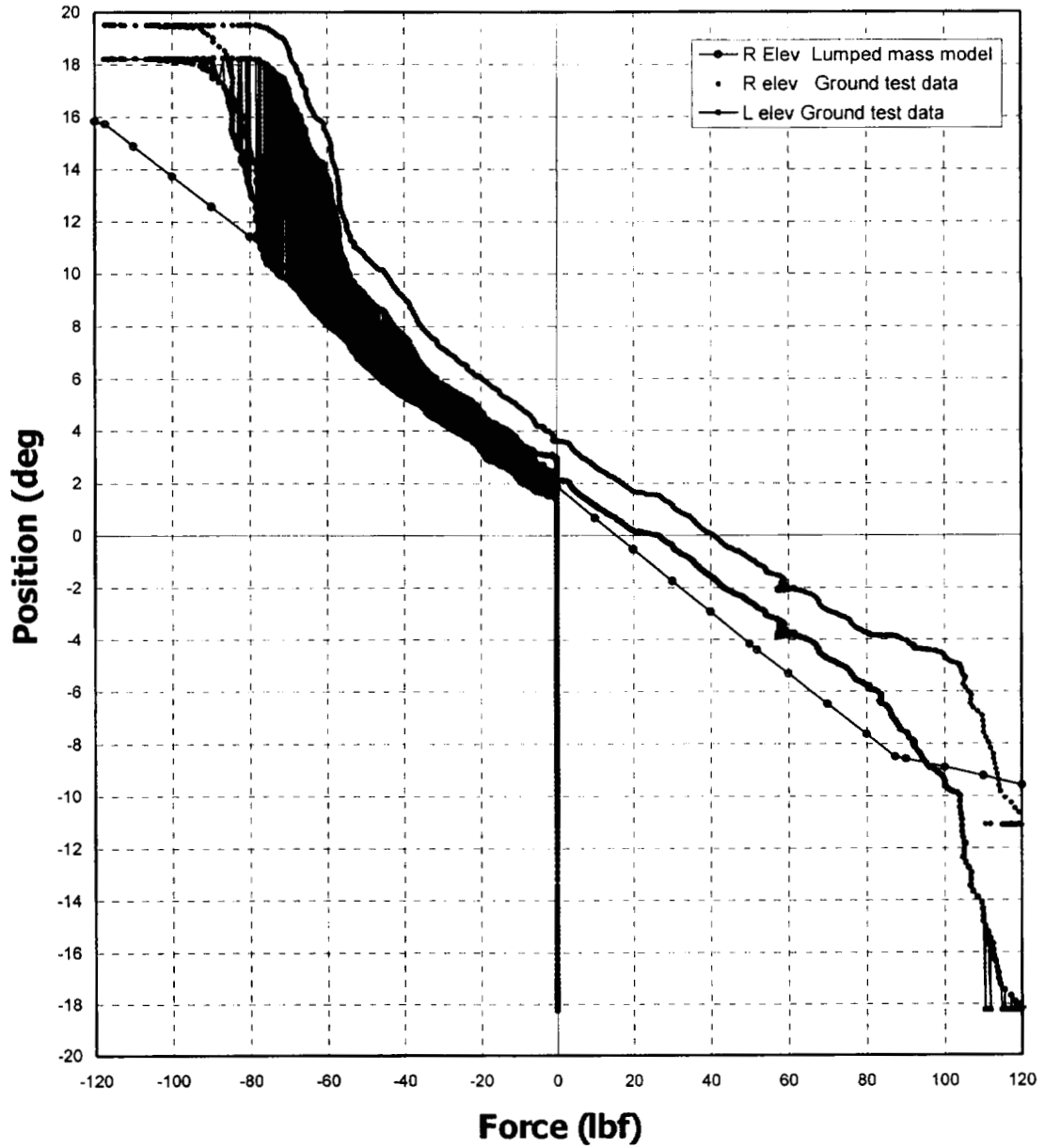


Figure 6. Elevator Deflection from Ground Test C and Analytical Model  
 Single PCA Control Valve Jam on the Right Elevator, 770 psi Feel Pressure, Pilot  
 Control Sweep

# EgyptAir 990 Elevator Blowdown Angles, Dual PCA Failure Scenario

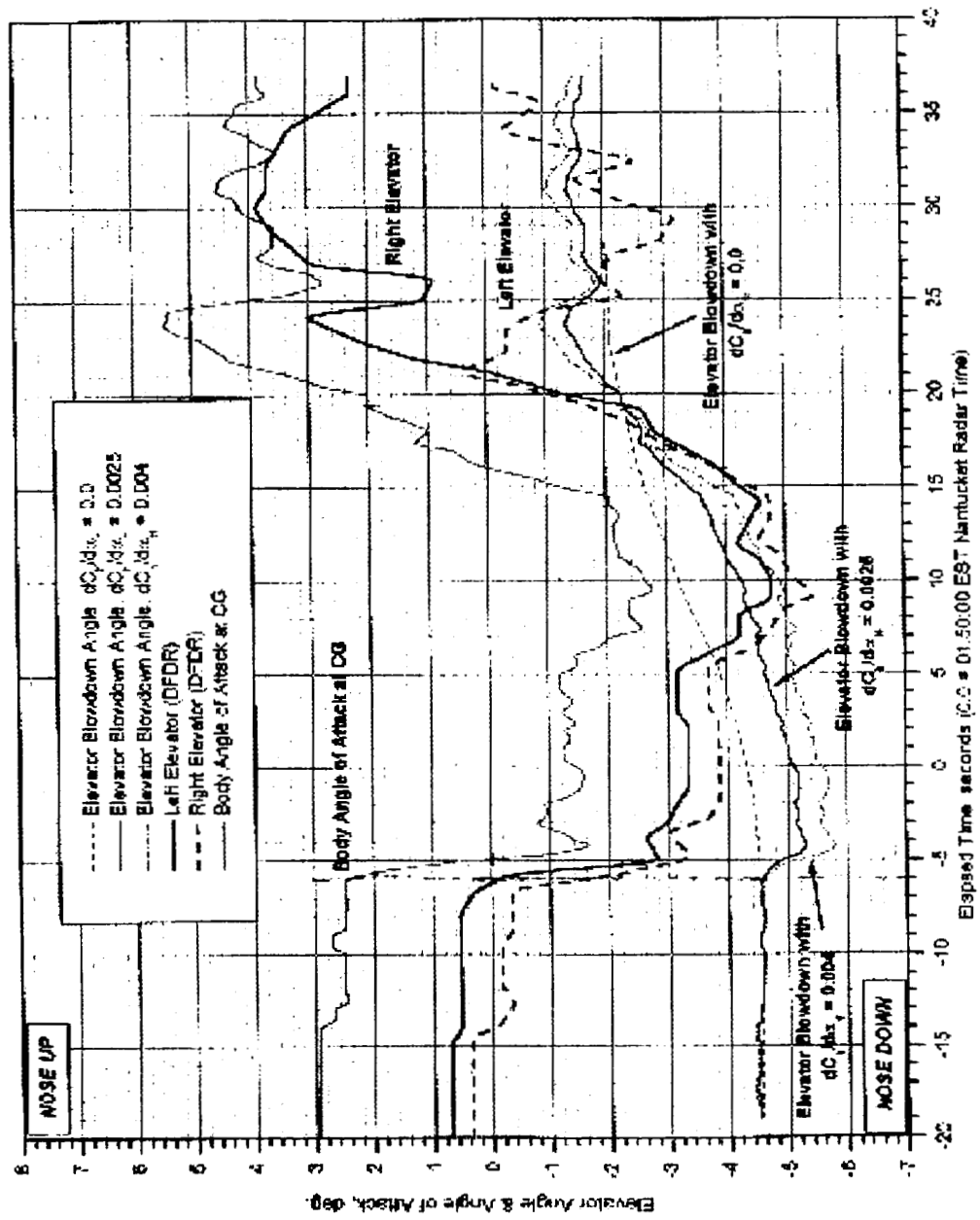


Figure 7. Expected Elevator Deflection as a Result of Dual PCA Valve Jam Failure (Produced by the NTSB Performance Group Chairman)

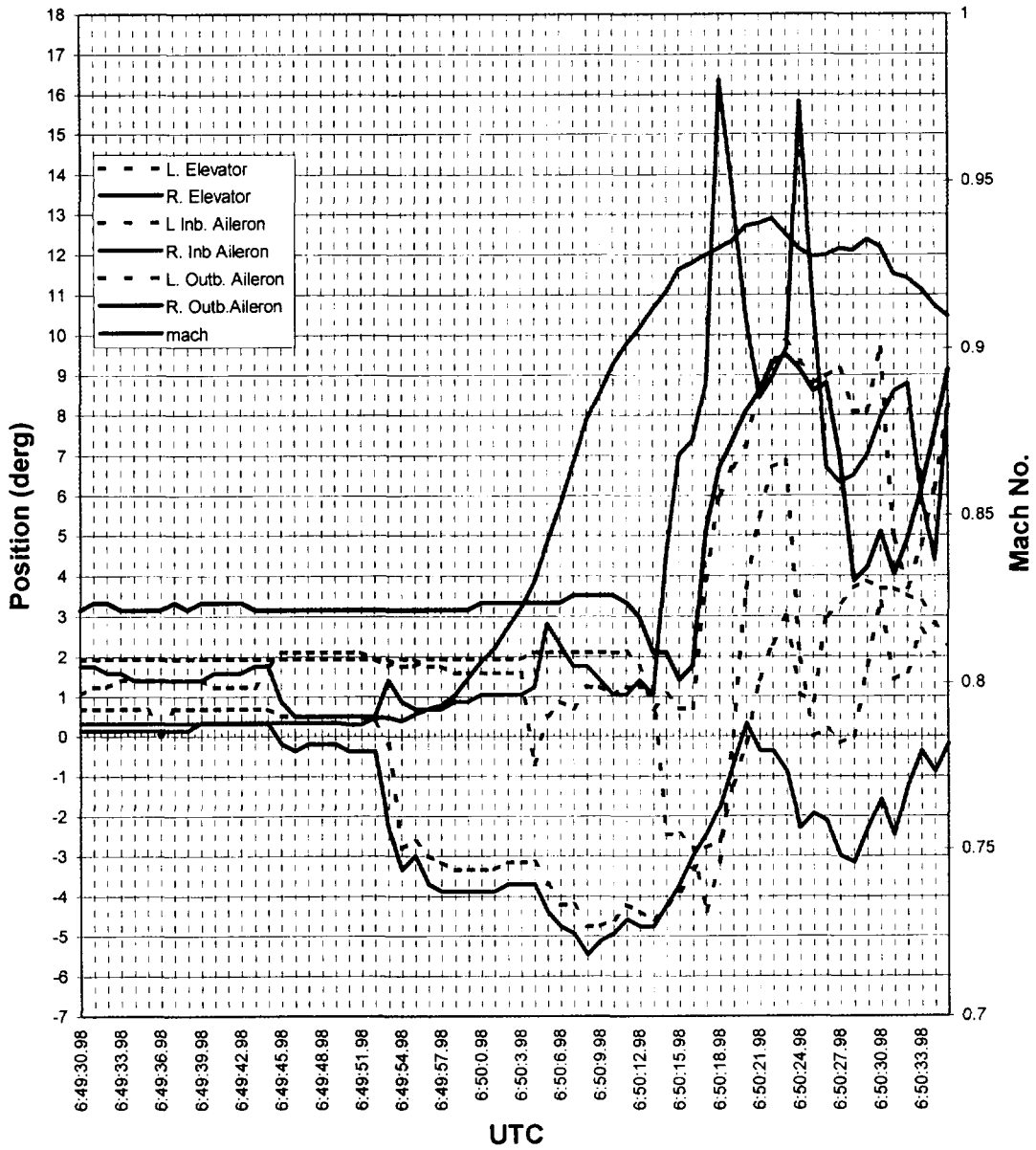


Figure 8. FDR Elevator and Aileron Deflection and Derive Mach Number

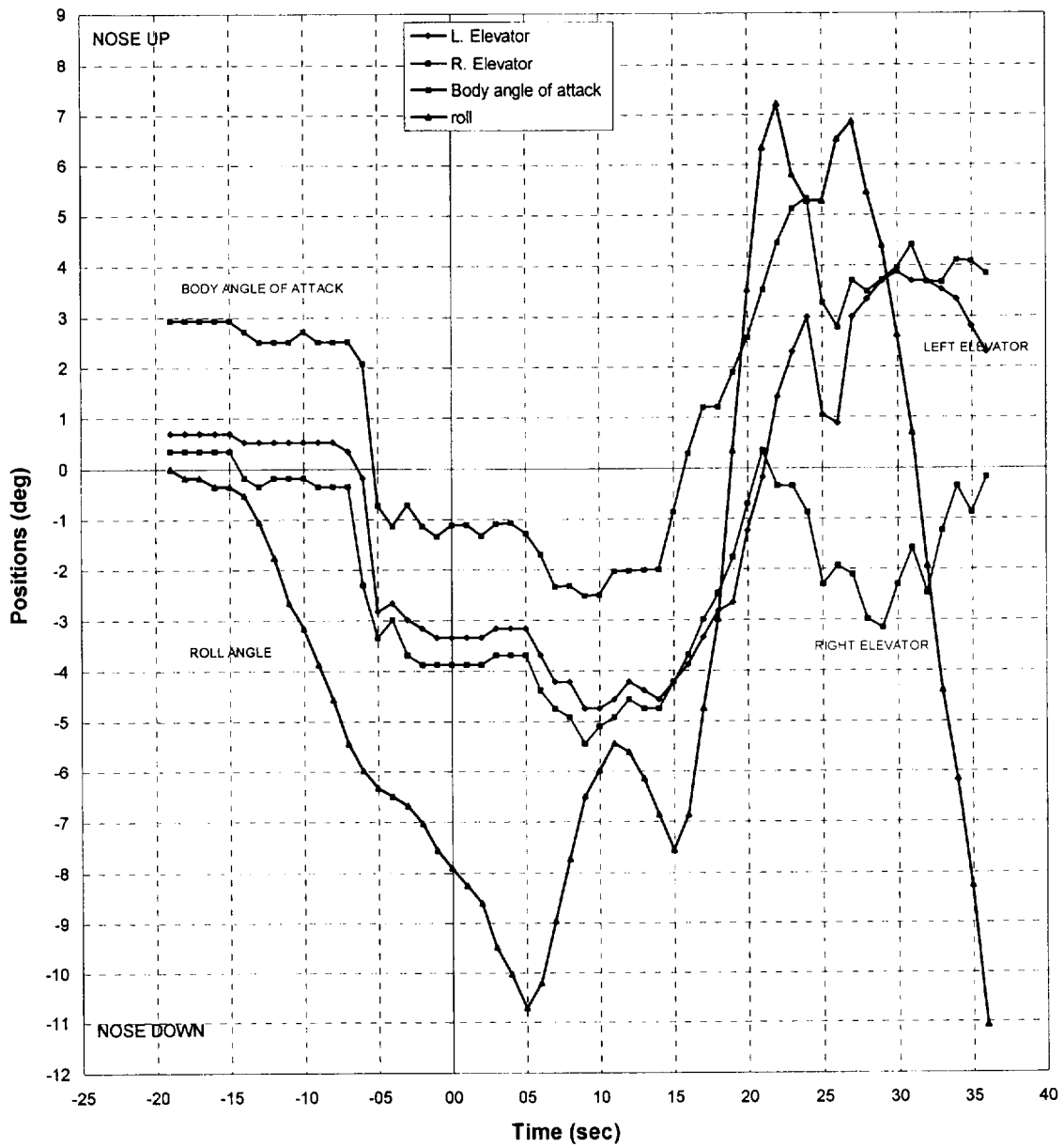


Figure 9. FDR Roll Angle and Derived Body Angle of Attack

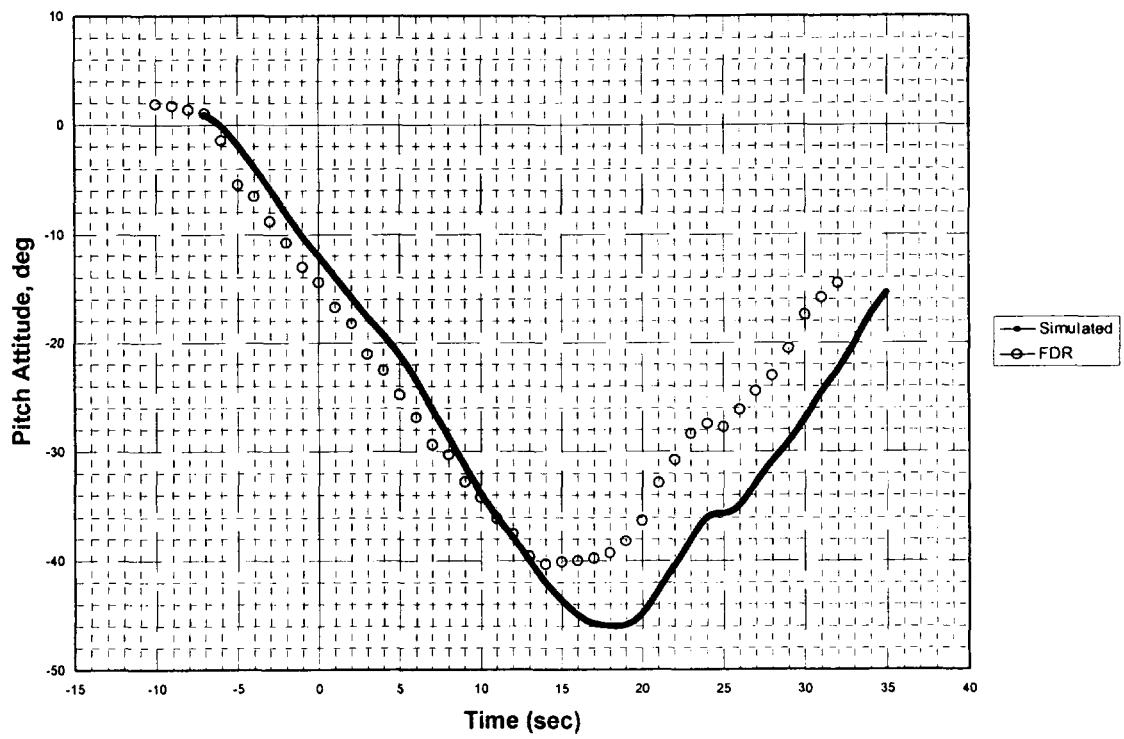


Figure 10. Pitchover Simulation, Right Elevator as Recorded on the FDR



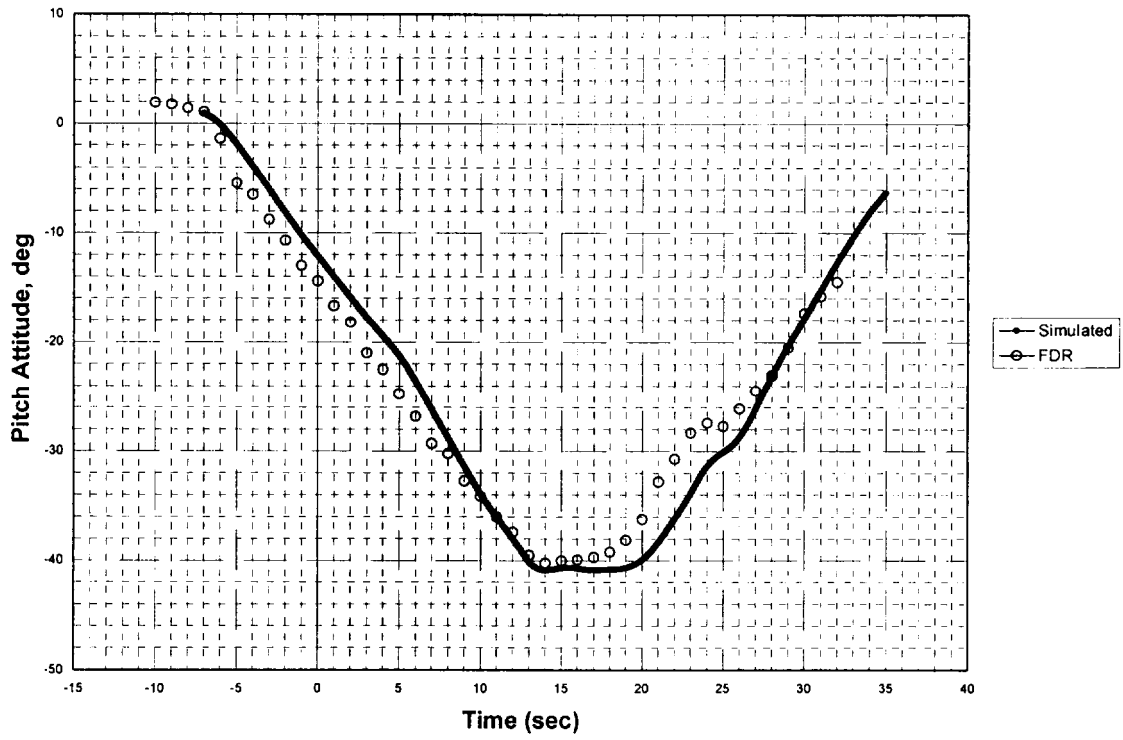


Figure 11. Pitchover Simulation, Right Elevator Missing

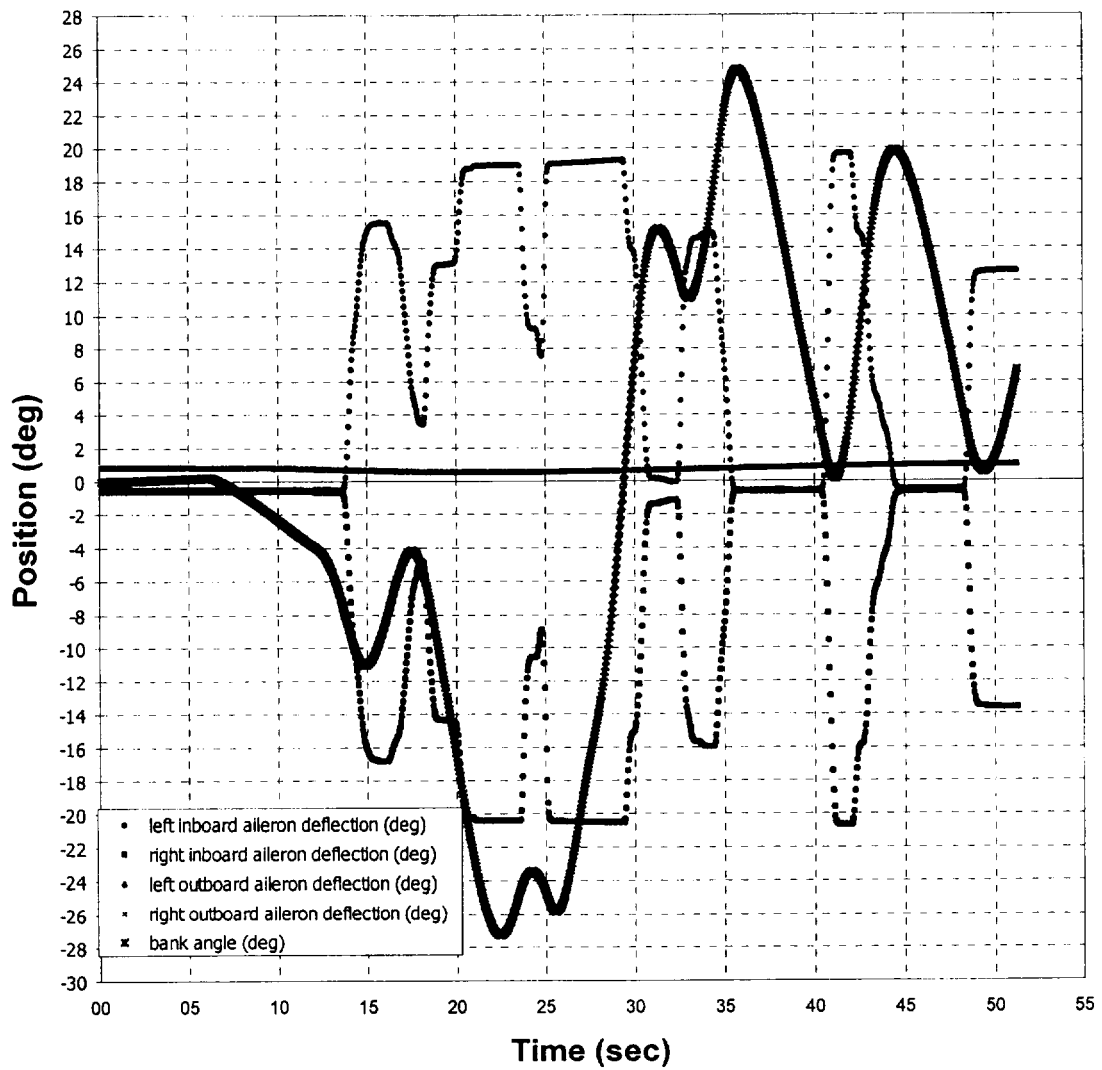


Figure 12. Aileron Deflection and Bank Angle from Data Recorded at the Second E-Cab Simulation Session

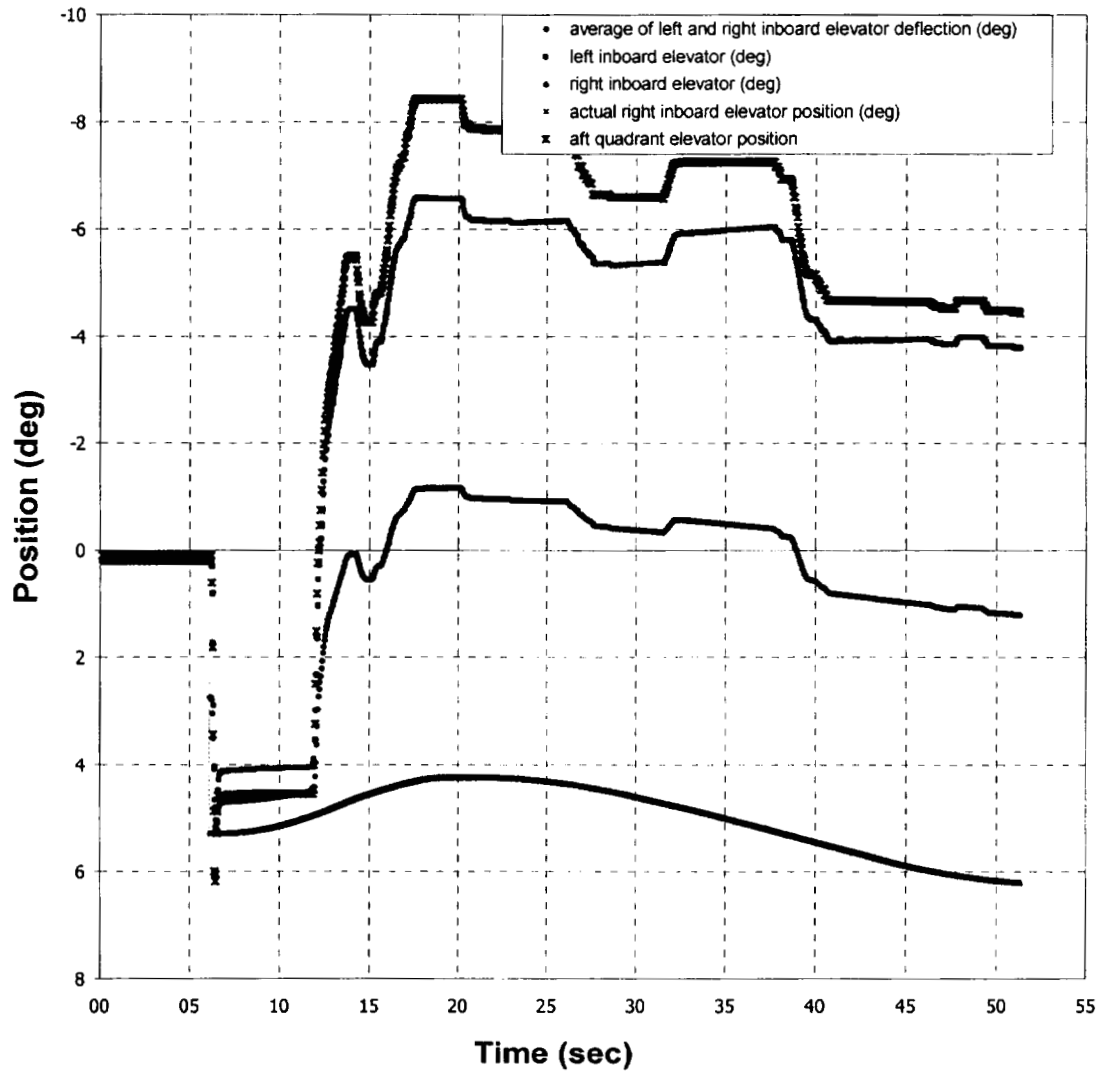


Figure 13. Elevator Deflection from Data Recorded at the Second E-Cab Simulation Session

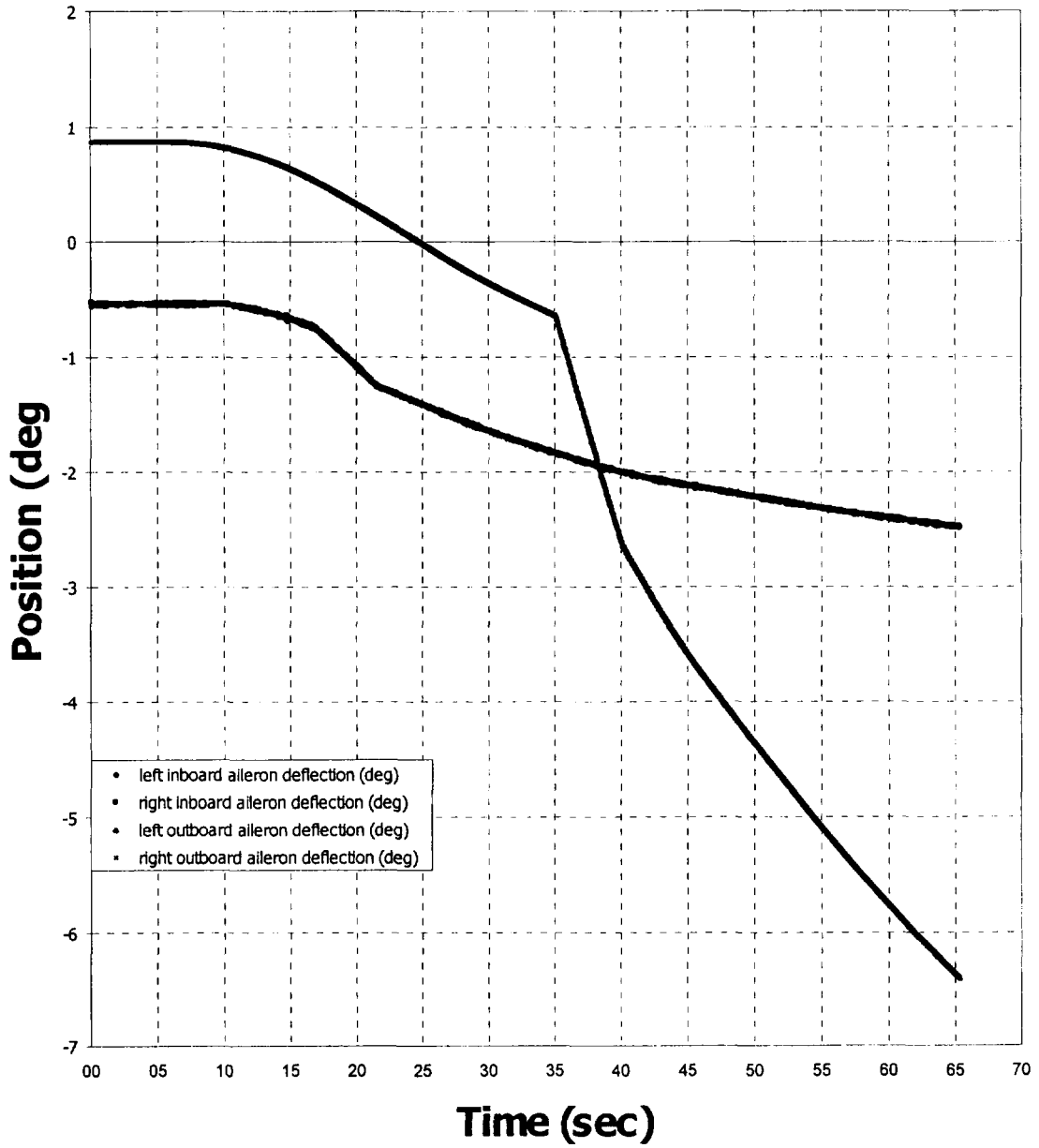


Figure 15. Aileron Position from B-767 Ground Test Results Extracted from Boeing CD

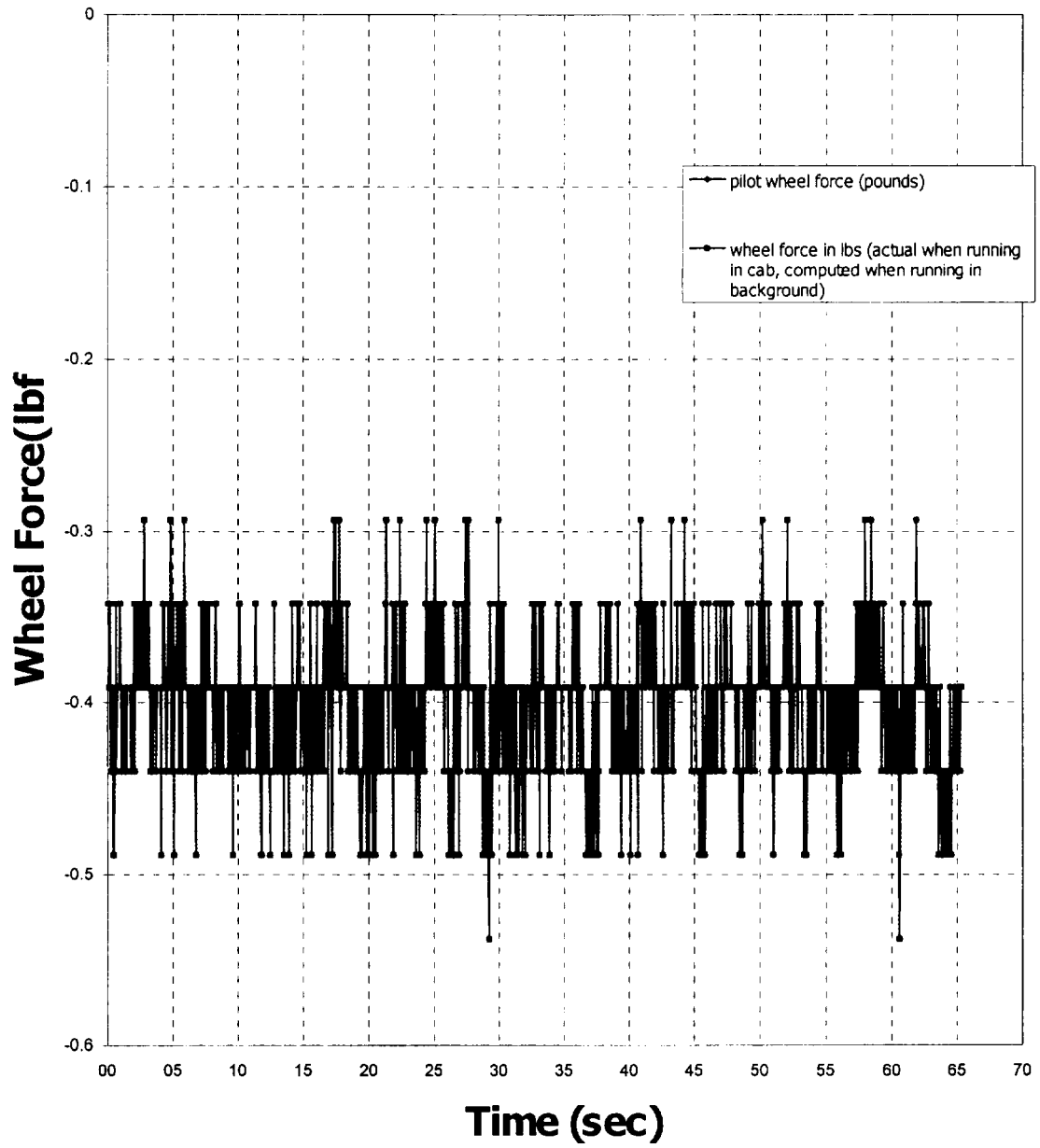


Figure 14. Wheel Force from B-767 Ground Test Results Extracted from Boeing CD

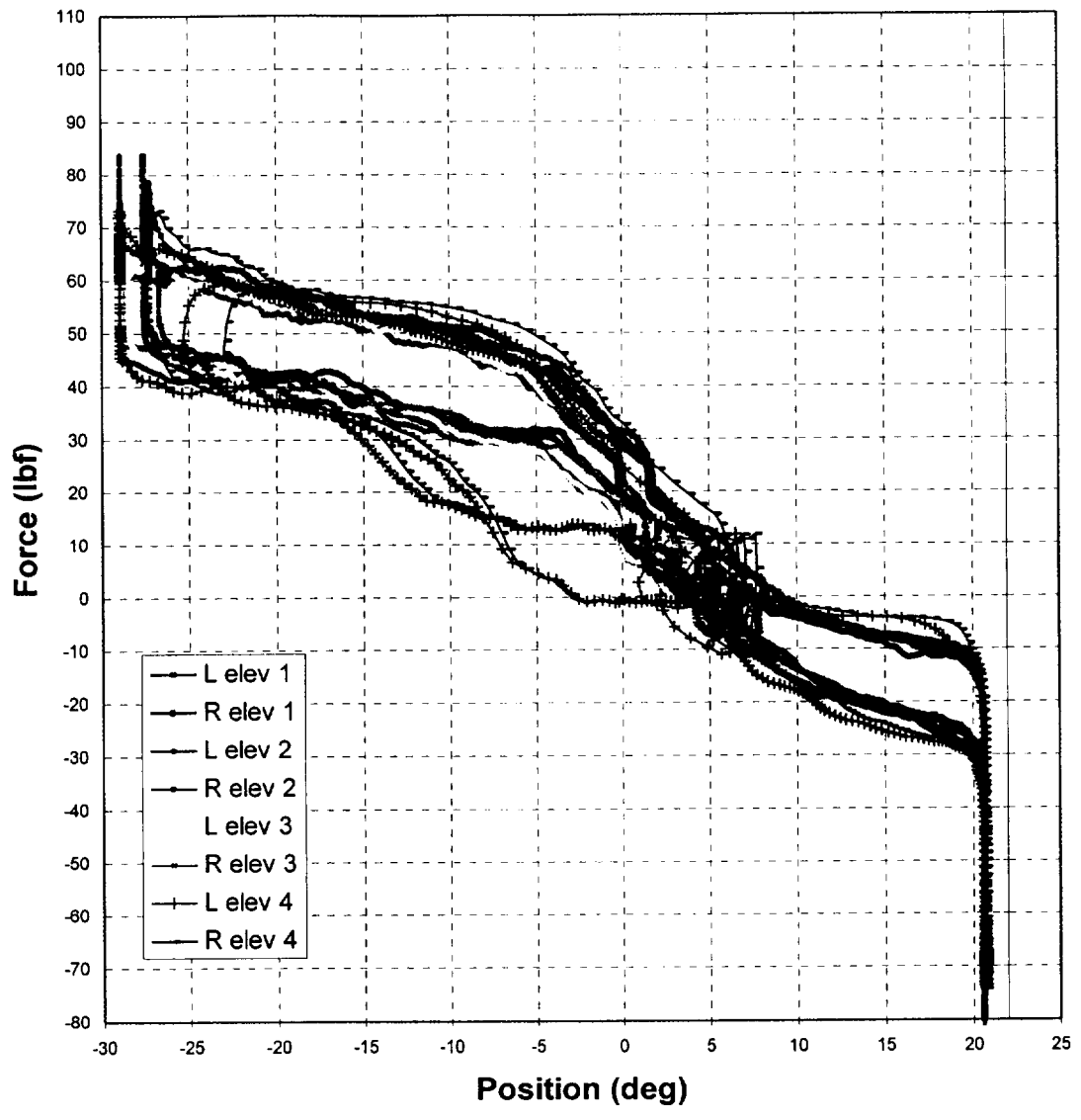


Figure 16. B-767 Ground Test Data, Single PCA Jam, Base Elevator Feel Pressure, Pilot Column Sweep

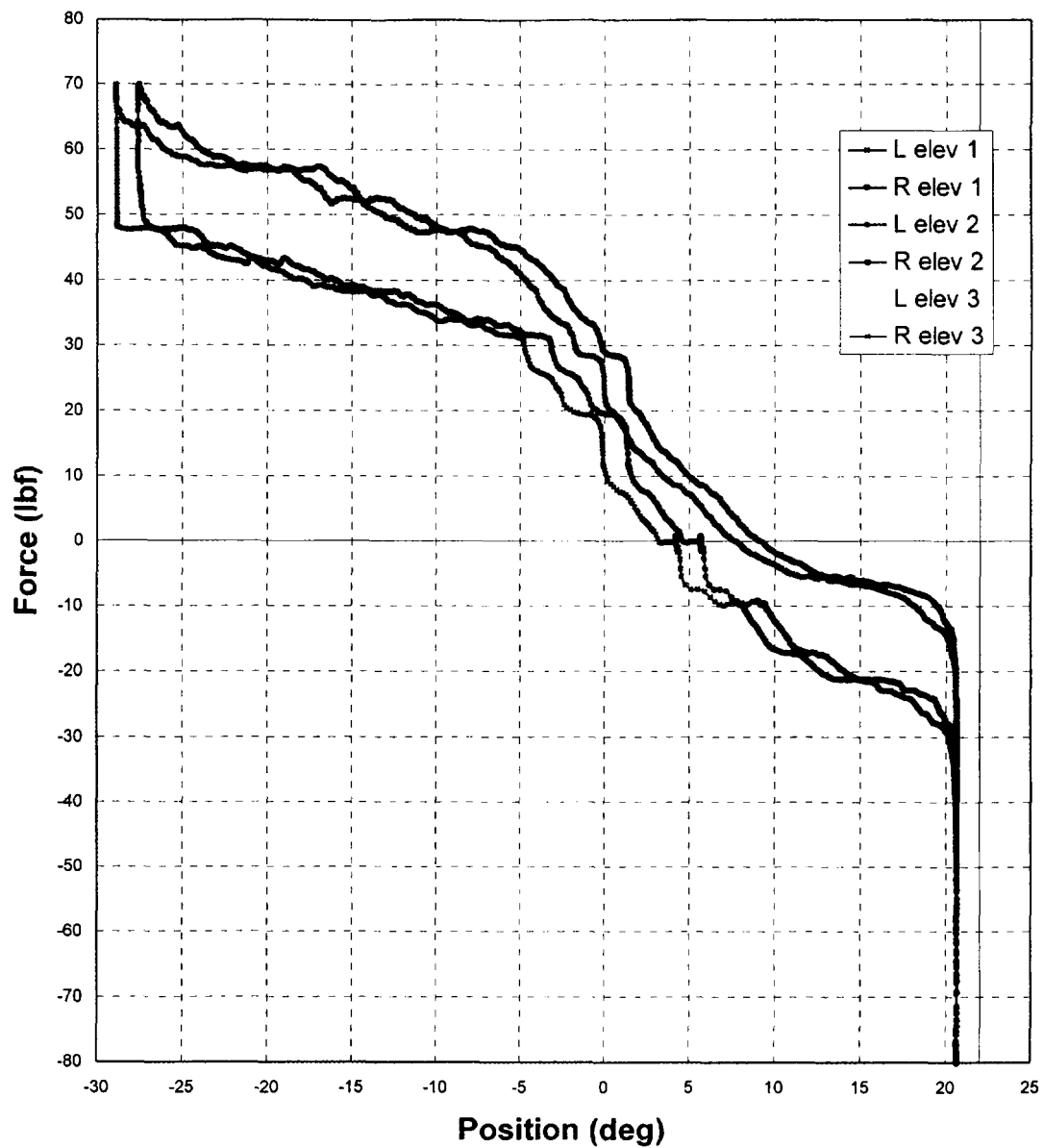


Figure 17. B-767 Ground Test Data, Single PCA Jam, Base Elevator Feel Pressure, First Officer Column Sweep

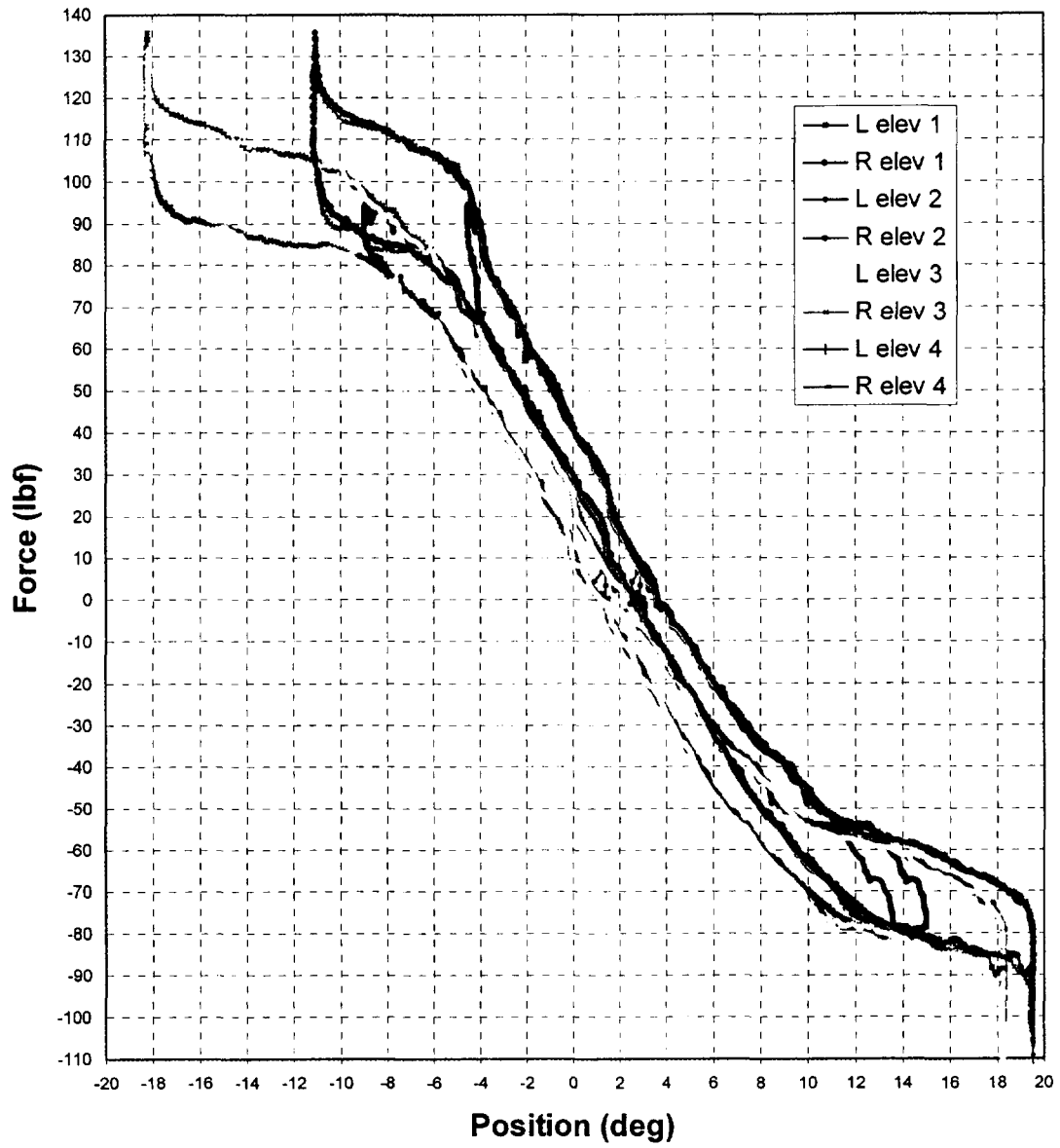


Figure 18. B-767 Ground Test Data, Single PCA Jam, 770 psi Elevator Feel Pressure, Pilot Column Sweep



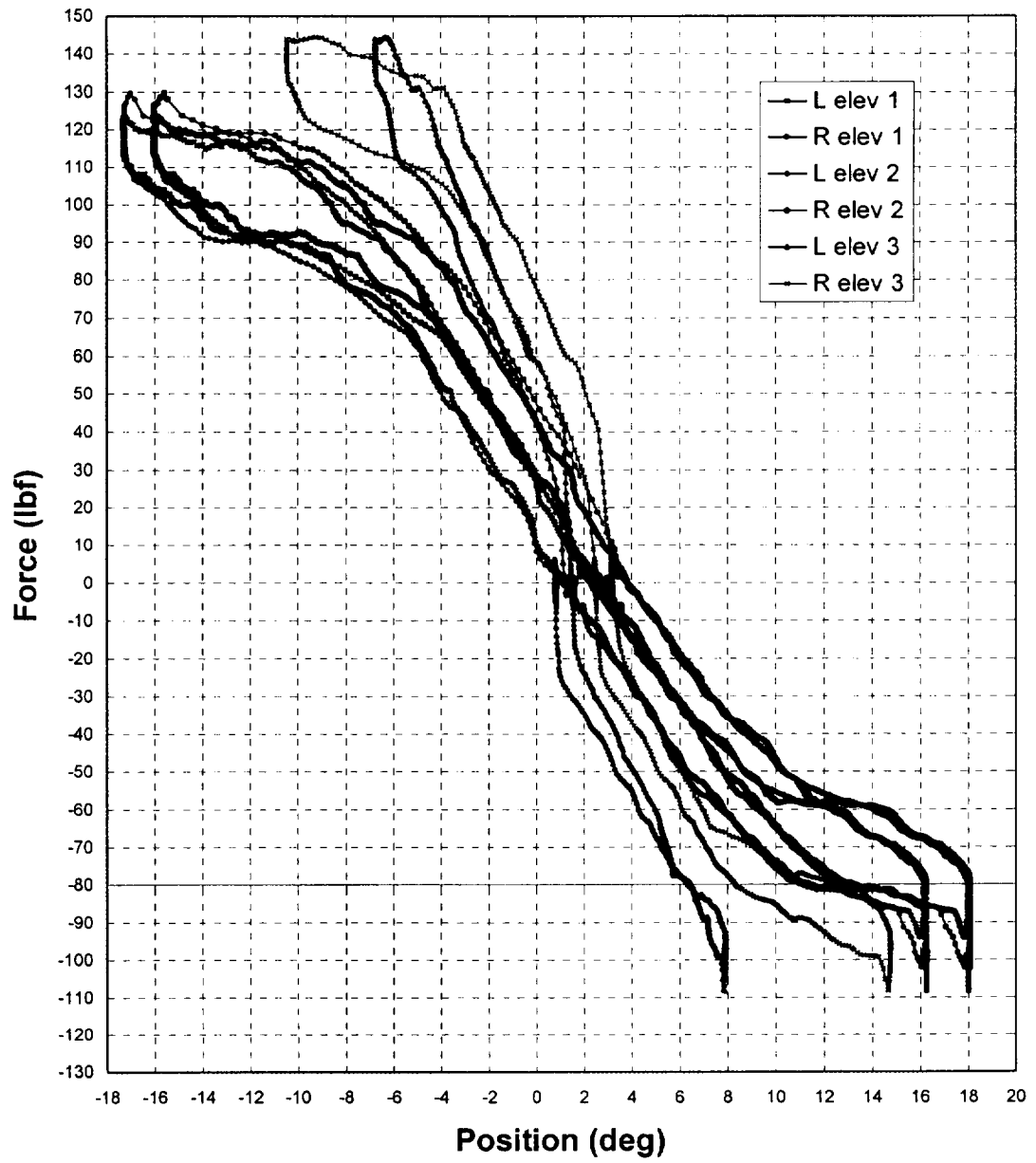


Figure 19. B-767 Ground Test Data, Single PCA Jam, 770 psi Elevator Feel Pressure, First Officer Column Sweep

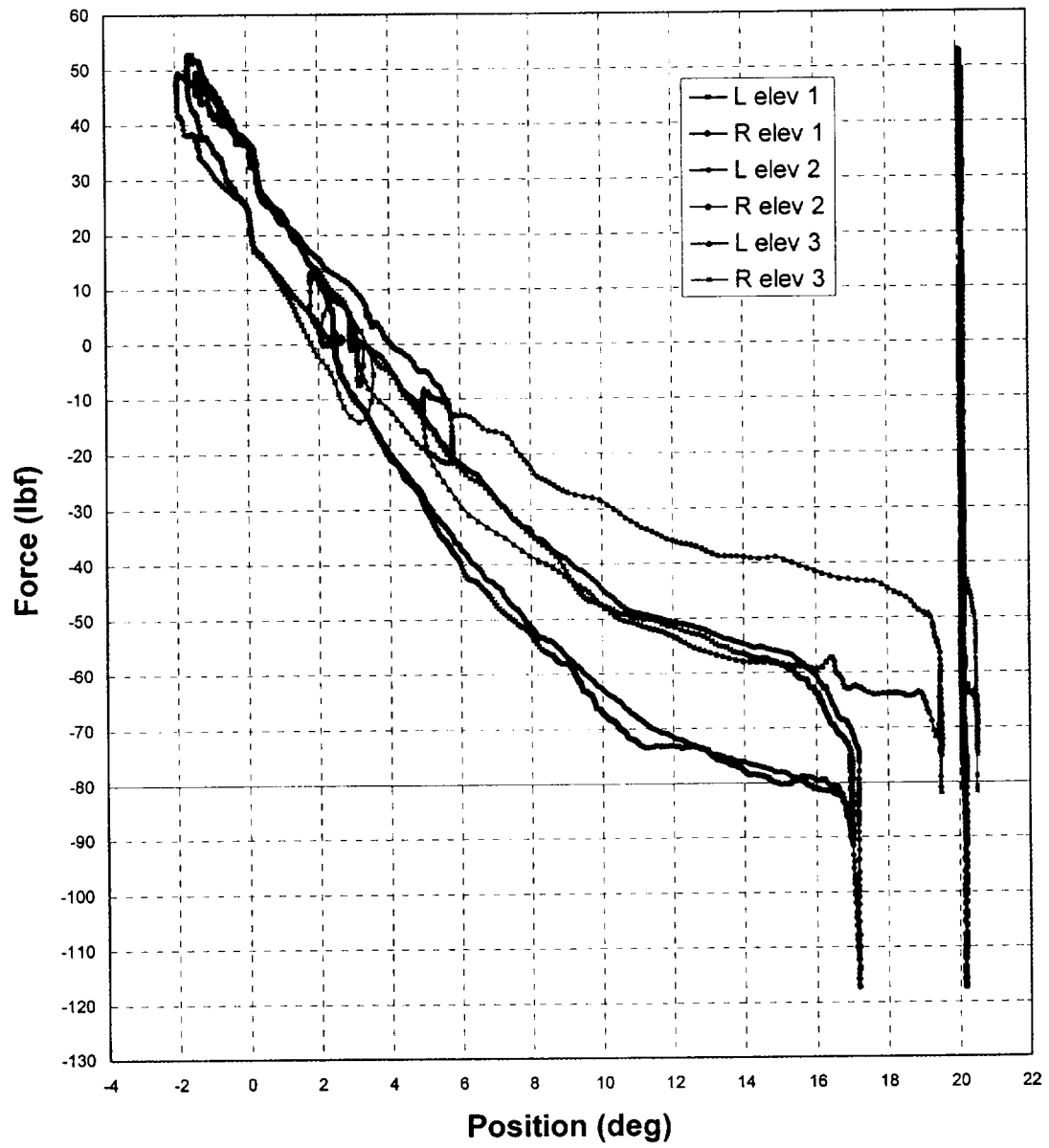


Figure 20. B-767 Ground Test Data, Single PCA Jam and One PCA Disconnected, 770 psi Elevator Feel Pressure, First Officer Column Sweep.

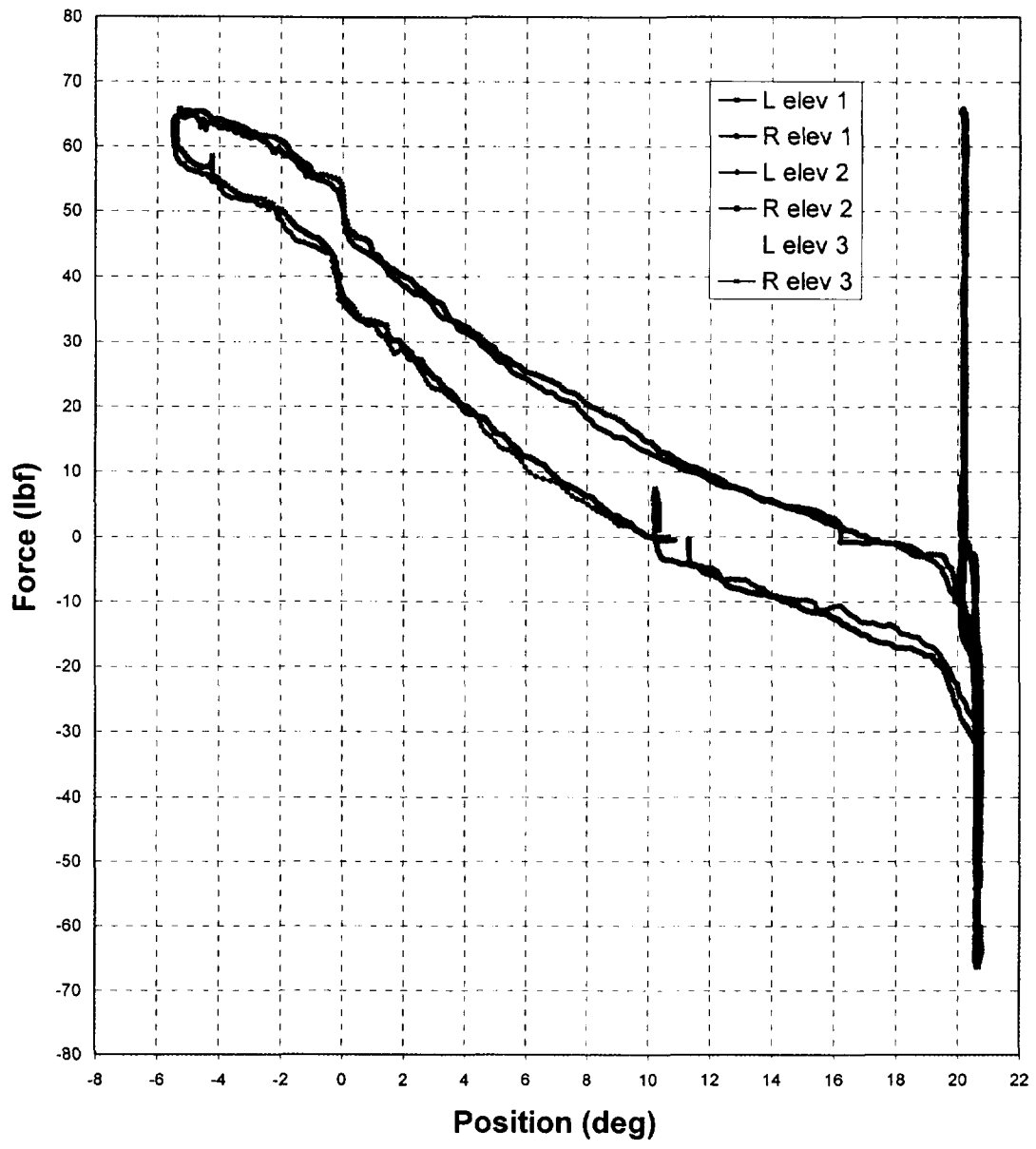


Figure 21. B-767 Ground Test Data, Dual PCA Jam, Base Elevator Feel Pressure, Pilot Column Sweep.

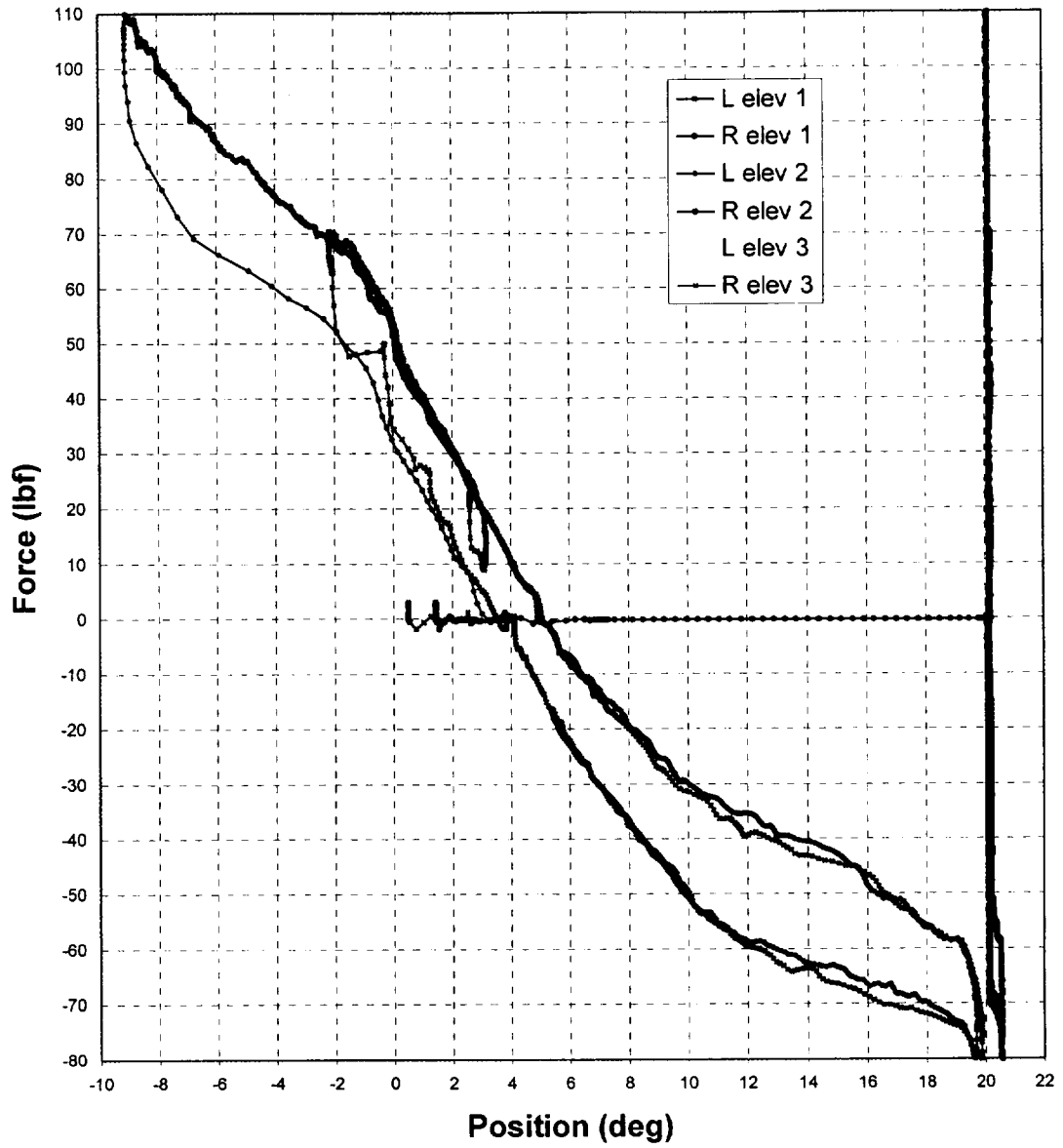


Figure 22. B-767 Ground Test Data, Dual PCA Jam, 770 psi Elevator Feel Pressure, Pilot Column Sweep

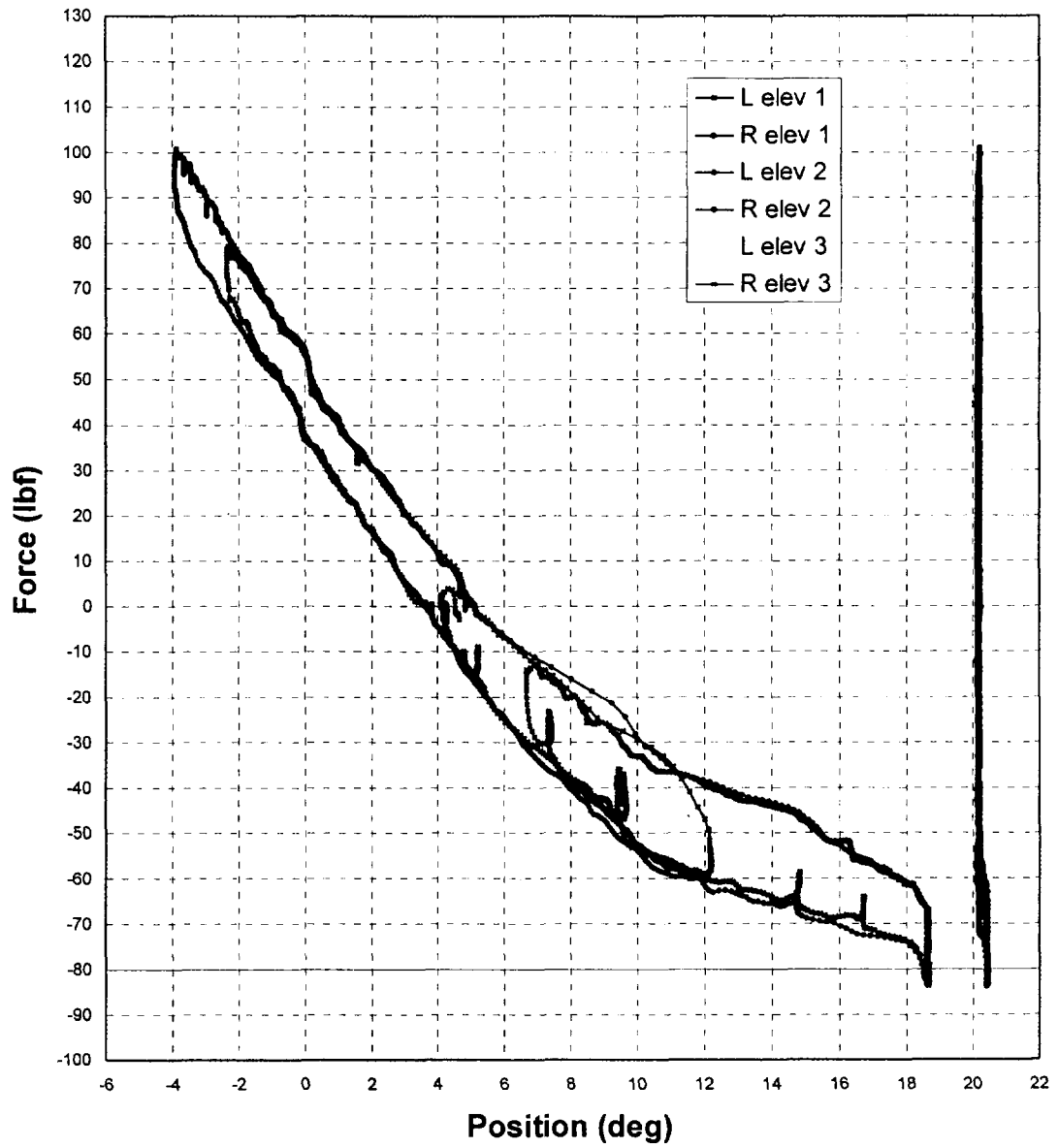


Figure 23. B-767 Ground Test Data, Dual PCA Jam, 770 psi Elevator Feel Pressure, First Officer Column Sweep

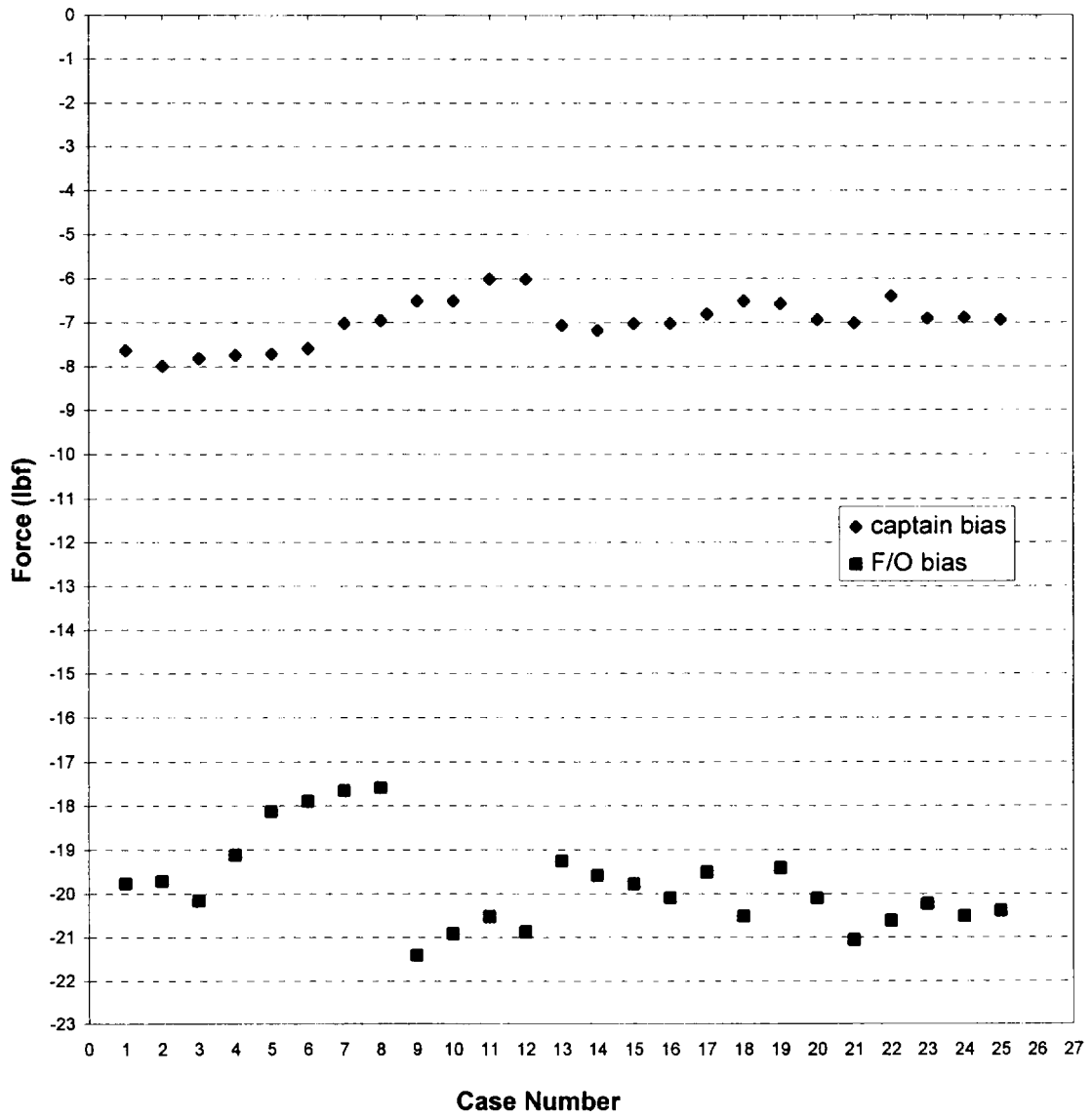


Figure 24. March Ground Test Data, Bias Changes for Captain and First Officer Column Force Measurements

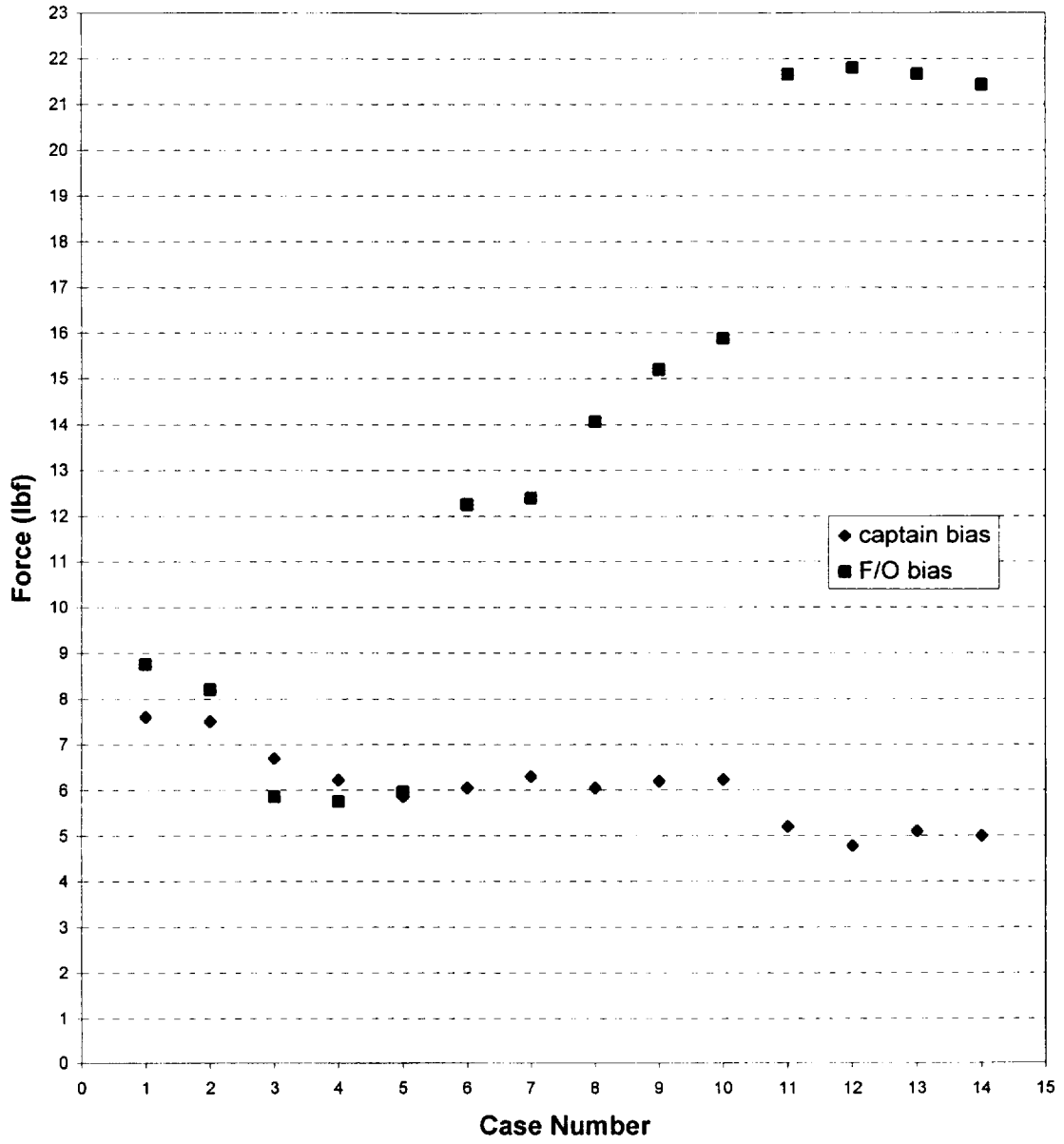


Figure 25. April Ground Test Data, Bias Changes for Captain and First Officer Column Force Measurements

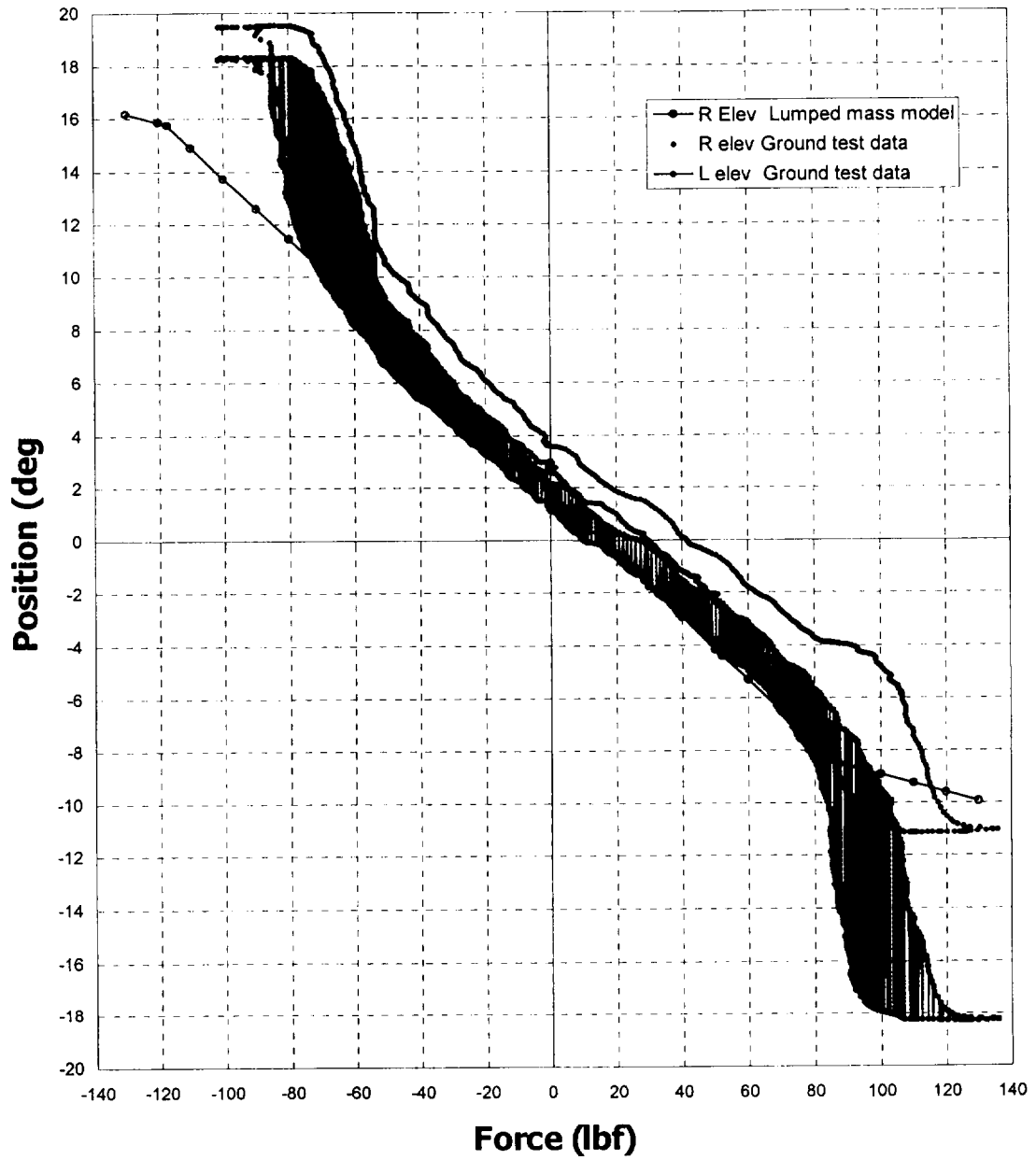


Figure 26. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Single PCA Jam, Condition A



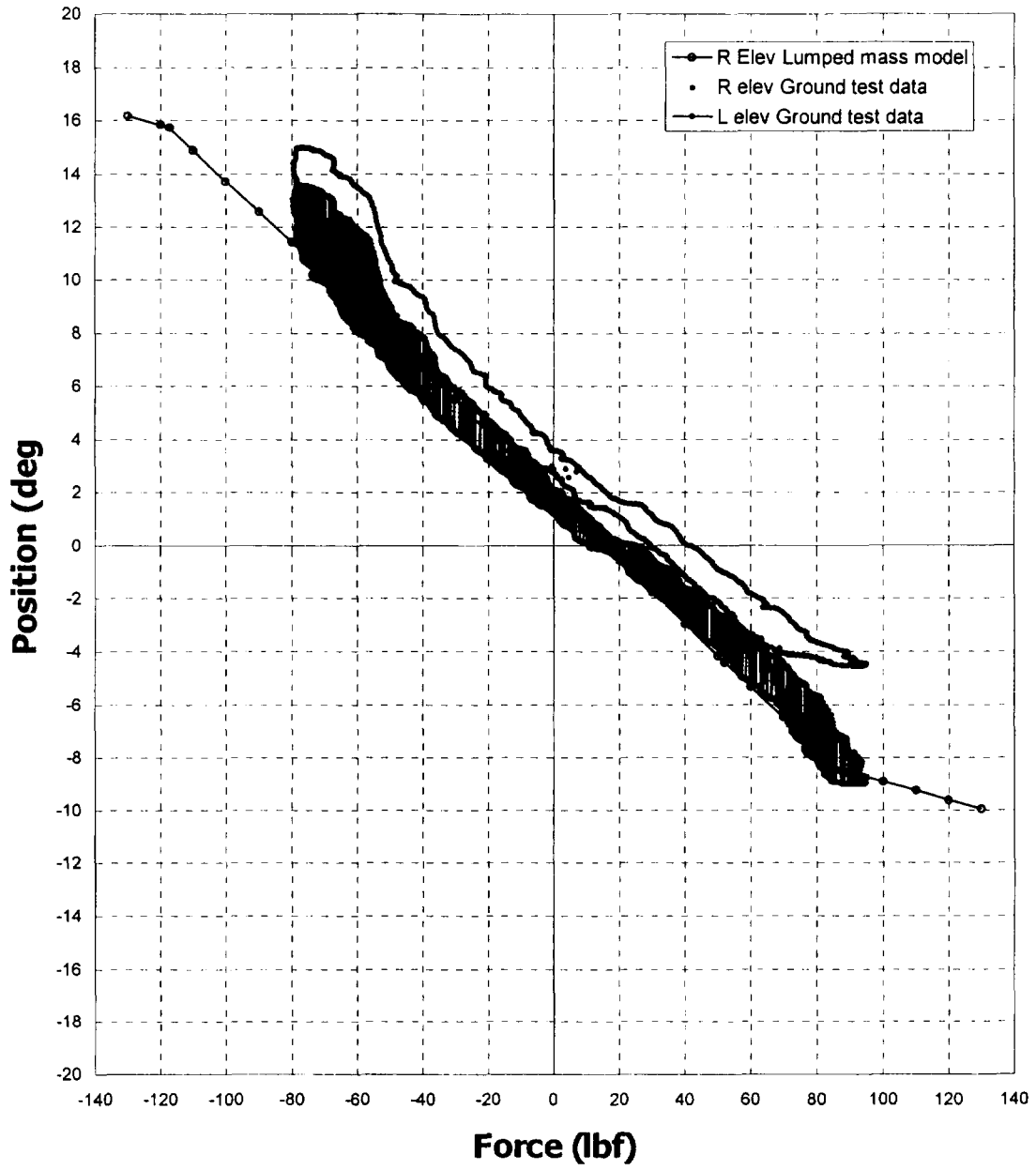


Figure 27. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Single PCA Jam, Condition B

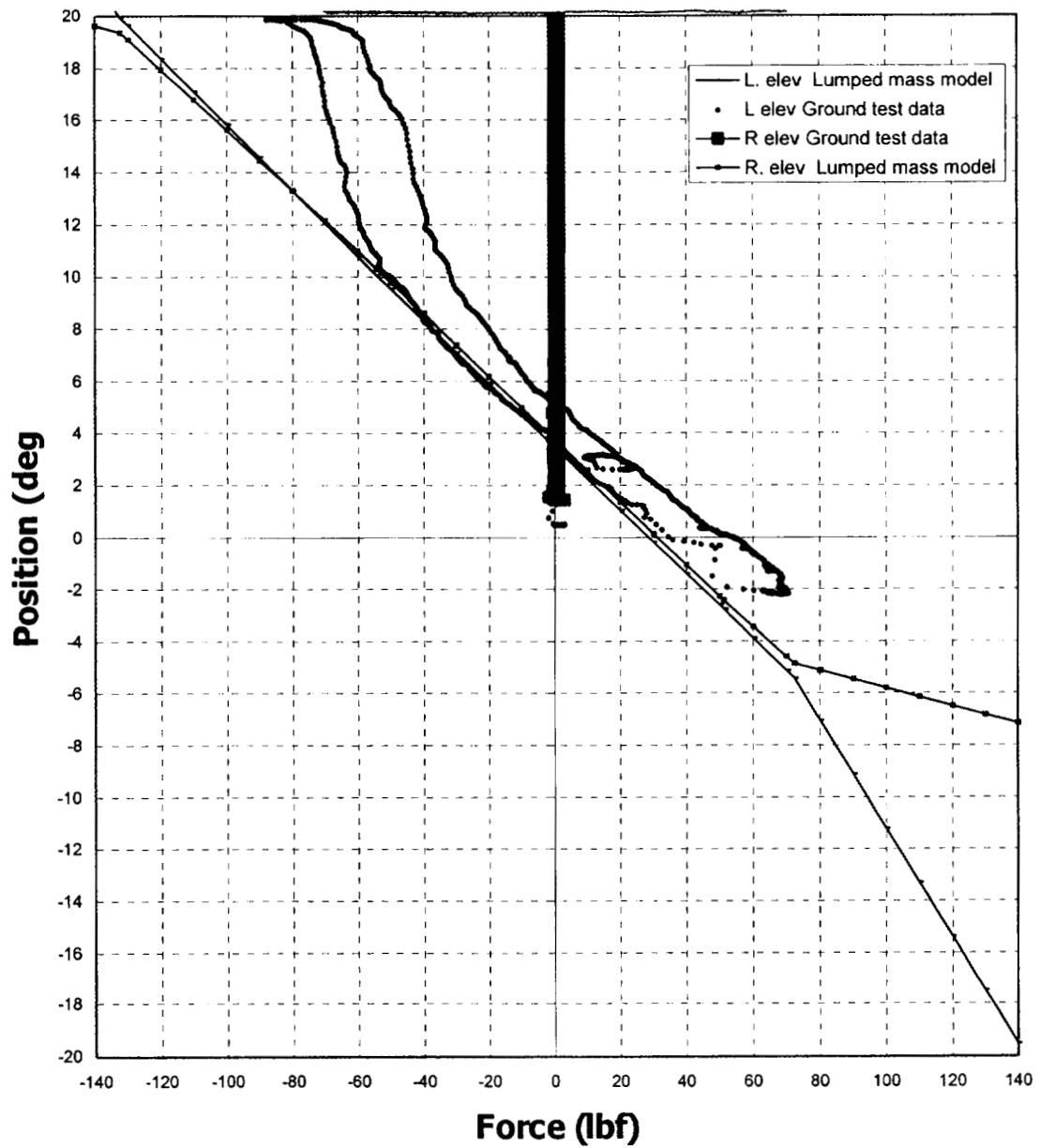


Figure 28. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Dual PCA Jam, 770 psi Feel Pressure, Pilot Control Sweep, Condition A

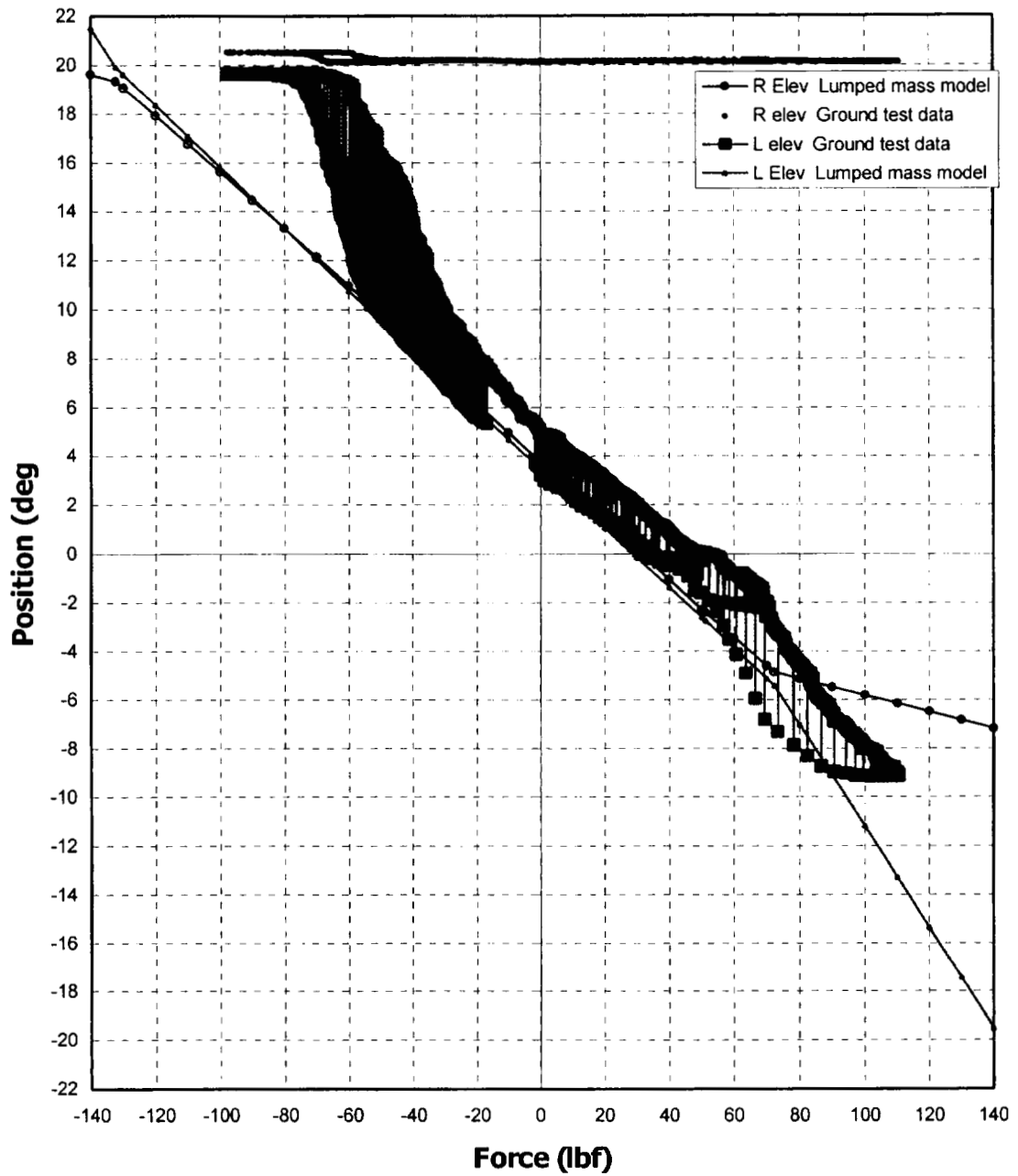


Figure 29. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Dual PCA Jam, 770 psi Feel Pressure, Pilot Control Sweep, Condition B

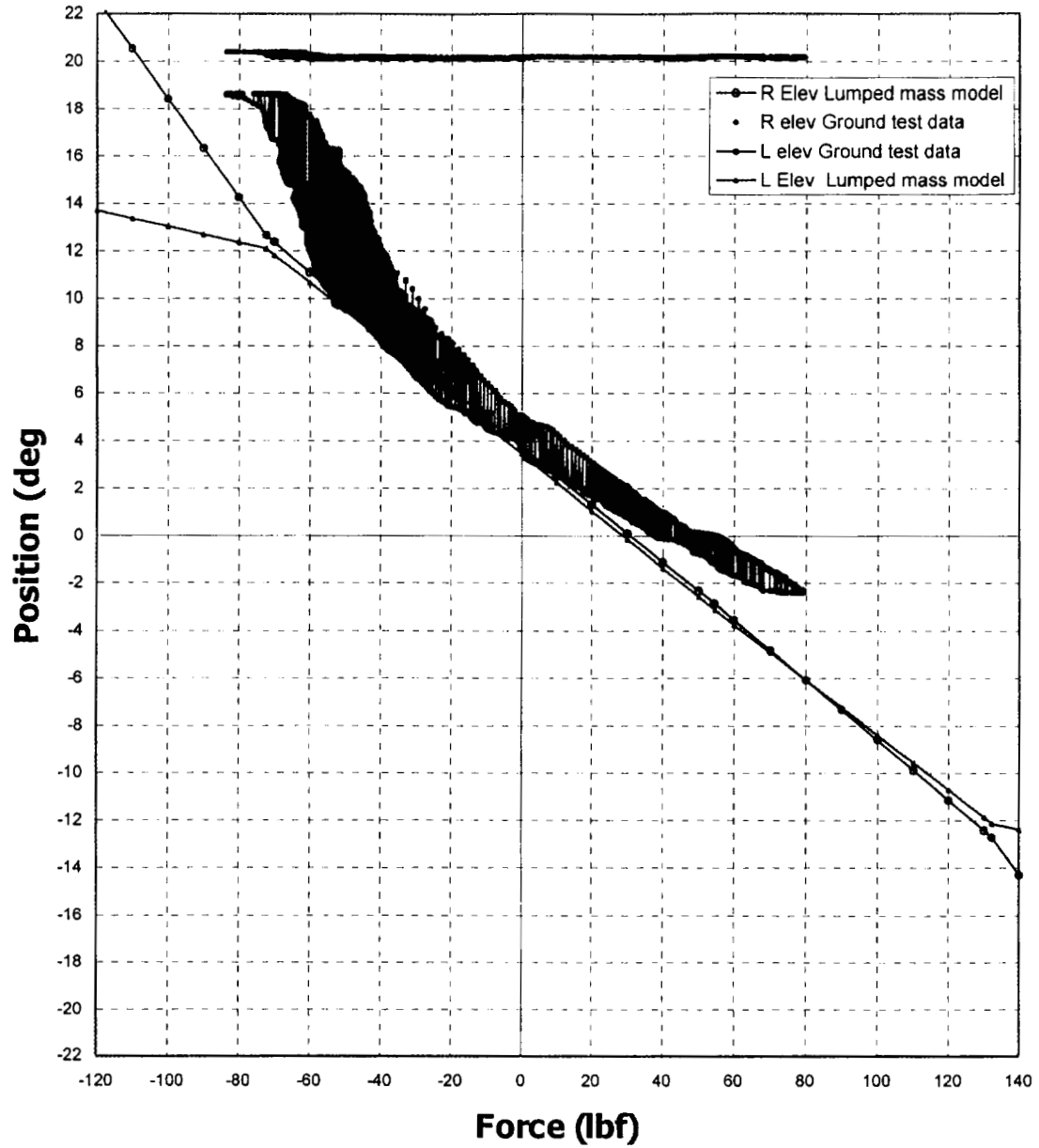


Figure 30. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Dual PCA Jam, 770 psi Feel Pressure, First Officer Control Sweep, Condition A

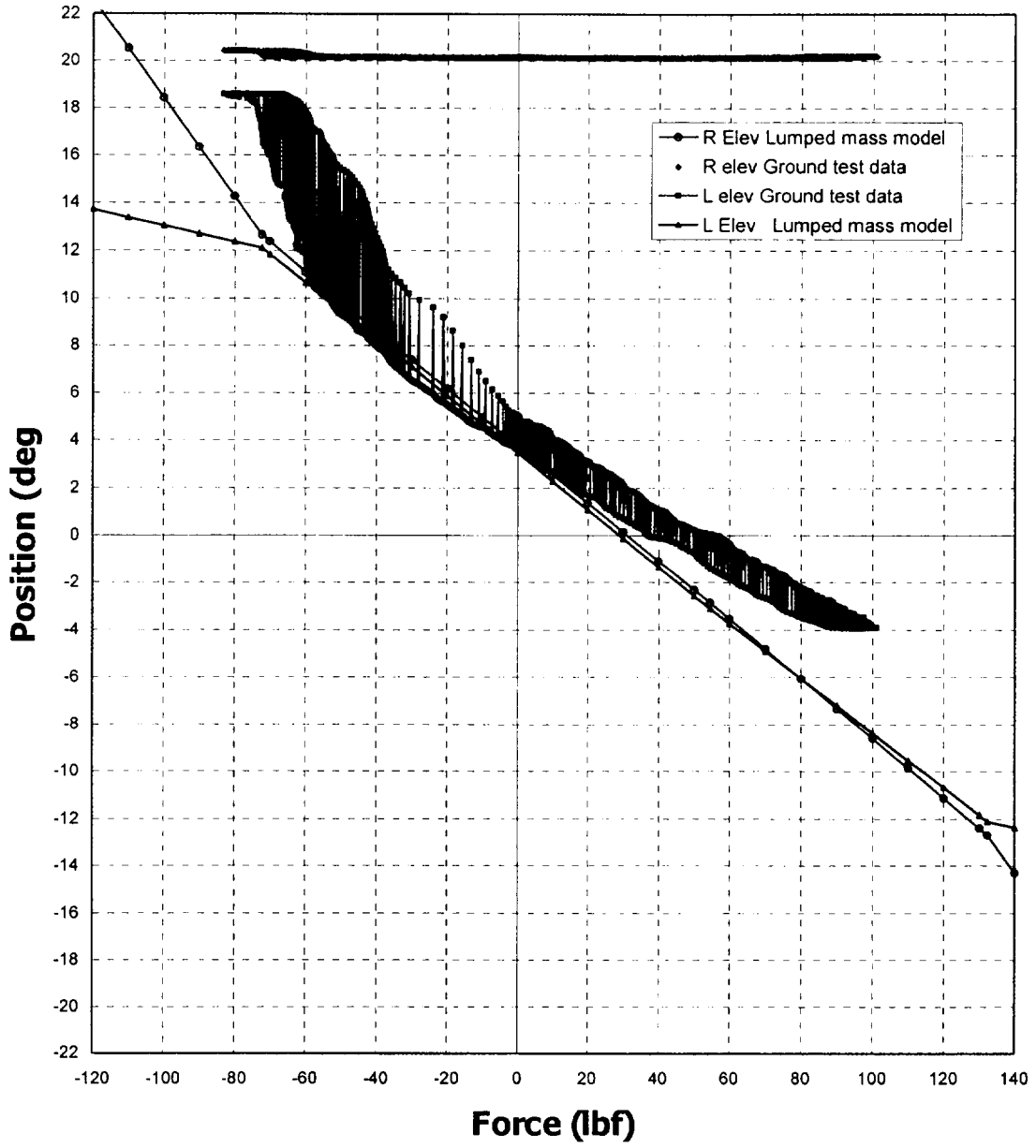


Figure 31. B-767 Ground Test Results Extracted from Boeing CD Compared to Boeing Mathematical Lumped Mass Elevator Model, Dual PCA Jam, 770 psi Feel Pressure, First Officer Control Sweep, Condition B

NTSB Note: The Boeing submission of October 31, 2000 originally attached to this letter is available in its entirety as a separate docket item