DOCKET NO. **SA - 510**

EXHIBIT NO. **13 G**

NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C.

Kinematic Study and Backdrive Package

Boeing Commercial Airplane Group
P.O. Box 3707
Seattle, WA 98124-2207

(1)

January 10, 1995
B-U01B-15081-ASI

Mr. Thomas Jacky, RE-60
National Transportation Safety Board
490 L'Enfant Plaza SW
Washington DC 20594-2000

Subject: US Air 737-300 Accident, N513AU/PP033 Near Pittsburgh, September 8, 1994 - Kinematic Analysis/Simulation Match

BOEING

Reference: Your letter to Rick Howes, items 2 and 3, December 1, 1994

Dear Mr. Jacky:

As requested in items 2 and 3 of the reference letter we have enclosed the kinematic analysis of data extracted from the subject flight data recorder (FDR) and the simulation match (backdrive) of the FDR.

Appendix B (Computer Code and Data used in the Kinematic Analysis) of enclosure A that is being forwarded to the NTSB by or with this correspondence is for the exclusive purpose of supporting investigative activities, is considered proprietary to The Boeing Company, and is being provided on a confidential basis. We do not authorize dissemination of this material to the public. This data provided should be returned to Boeing immediately following use by the NTSB, including any copies thereof which the NTSB may be required to make in the course of its review. Boeing does not authorize the NTSB to retain any portion of the materials being supplied.

If you have questions, please contact Rick Howes, ([redacted] or me.

Very truly yours,

FLIGHT TEST

[redacted]

John W. Purvis
Director, Air Safety Investigation
Org. B-U01B, M/S 14-HM
Telex 32-9430, STA DIR PURVIS
[redacted]

Enclosures:

A. Boeing Kinematic Analysis of Data Extracted from the USAir, Flight 427 Flight Data Recorder
B. Boeing 737-300 Simulation Match of USAir 427 FDR Data

Kinematic Analysis of Data Extracted from the USAir, Flight 427 Flight Data Recorder

Summary:

Using the kinematic equations of motion, data from the USAir 427 flight data recorder (FDR) have been analyzed, providing estimates of sideslip angle, angle-of-attack and other parameters not directly measured or recorded. These data were then further analyzed to provide estimates of the total airplane aerodynamic coefficients. External factors such as FDR errors, winds aloft, wake turbulence, and structural damage are not known and can not be separated from the analysis. The estimated coefficients include all of these external factors, plus the effects of any unknown airplane control deflections, and deficiencies in the simulator aerodynamic model.

Except for column, the actual control deflections from USAir 427 are unknown. To aid in the understanding of the flight scenario, the estimated yawing and rolling moment coefficients have been converted to equivalent rudder and wheel deflections, using the flight characteristics of the 737-300.

Preliminary results from this analysis were presented to the NTSB Performance Group in Seattle, Washington on October 12, 1994 and November 2, 1994.

Results of this study, and details of the analysis are presented and discussed in the enclosures.

Discussion

When analyzing sparse data sets, such as those that are typically available from aircraft flight data recorders, it is often necessary to estimate parameters which were not recorded, in order to better understand the flight scenario.

One method of doing this is to repeatedly run an engineering simulation of the aircraft through the accident scenario until an acceptable match of the known data has been achieved. This is a well accepted, valid approach to dealing with this type of problem, but tends to be very time consuming. The process involves iteratively predicting the airplane control deflections, or incremental aerodynamic coefficients, required to match the recorded angular rates, airspeed, altitude, load factor, etc. Each iteration also produces estimates of the various unknown motion parameters (sideslip, angle of attack, etc.). The difficulty with this procedure is that relatively small errors in the match tend to accumulate, limiting the fidelity of the final solution.

A second method -- the one used in this study -- divides the process into two steps, solving first for estimates of the unknown motion variables, and then independently solving for the related forcing functions.

Using the kinematic equations of motion, data from the USAir 427 flight data recorder (FDR) were analyzed, providing estimates of sideslip angle, angle-of-attack and other parameters not directly measured or recorded. These data were then further analyzed to provide estimates of the total airplane aerodynamic coefficients. External factors such as FDR errors, winds aloft*, wake turbulence, and structural damage are not known and can not be separated from the analysis. The estimated coefficients include all of these external factors, plus the effects of any unknown airplane control deflections, and deficiencies in the simulator aerodynamic model.

*Note: Calm air is critical to the success of this analysis. See Appendix A for more detail.

Except for column, the actual control deflections from USAir 427 are unknown. To aid in the understanding of the flight scenario, the estimated yawing and rolling moment coefficients have been converted to equivalent rudder and wheel deflections, using the flight characteristics of the 737-300.

A complete discussion of the kinematic analysis, including assumptions and limitations, is provided in Appendix A, followed by the pertinent computer code and data in Appendix B. A discussion of the aerodynamic analysis technique is provided in Appendix C.

Figures 1 and 2 show the basic airplane motion variables recorded on the USAir 427 FDR, along with the airspeed, altitude, angle-of-attack, sideslip angle, and other parameters estimated from the kinematic analysis. All data have been extrapolated to 160.04 seconds; the approximate time of impact. Also, the Euler angles (pitch, roll and yaw) have been enhanced between 149.9 and 151.0 seconds to provide smooth, continuous body axis angular rates through the region of the mathematical singularity (pitch ~ -90 degrees).

Figures 3 and 4 show the incremental aerodynamic coefficients which must be added to the simulation model, as a function of time, to match the motion data.

Figures 5 and 6 are identical to Figures 3 and 4 except that they show the equivalent rudder and wheel positions derived from the estimated yawing moment and rolling moment coefficients in those figures. As stated previously, these "equivalent control positions" represent the combined effects of data errors and all unknown, external factors acting on the aircraft. They are not the actual control positions. Figure 7 is the same as Figure 1 except that the time scale has been expanded and the equivalent rudder and wheel positions from Figure 5 are shown in place of the acceleration data.

Finally, Figures 8 and 9 are identical to Figures 5 and 6 except that the wheel is held constant at +85 degrees (max wheel effectiveness) following the peak at 143.5 seconds. This results in a residual rolling moment coefficient through the remainder of the data. Figure 10 is the same as Figure 7 except that it shows the same equivalent rudder and wheel positions as in Figure 8.

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USAir 427 Airplane Motion Data
With Appropriate Kinematic Corrections
As Described in the Attached Report

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737-300 | USAir 427 | PAGE

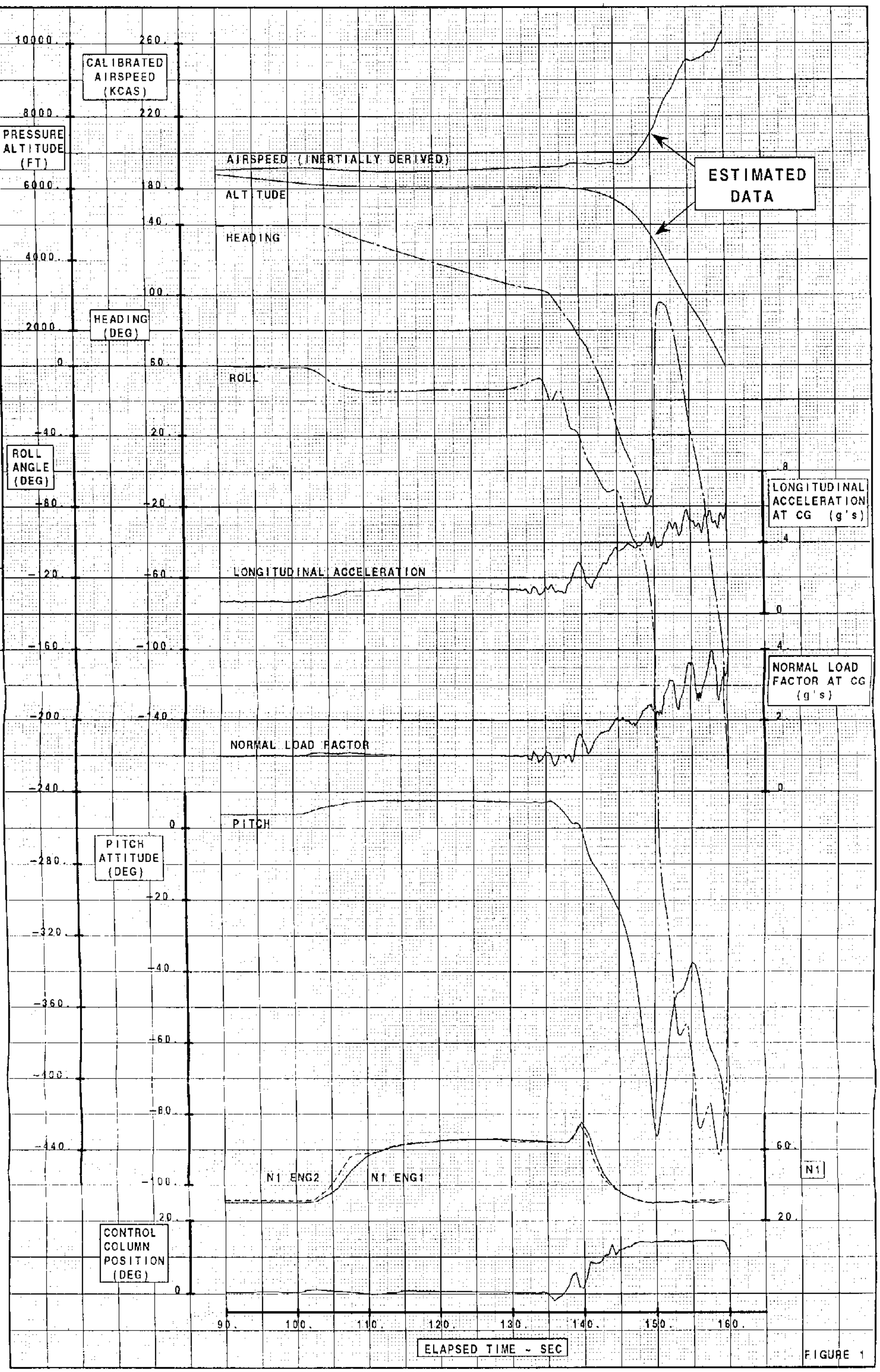

FIGURE 1

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Supplemental USAir 427 A/P Motion Data Derived using Kinematic Eqns. of Motion

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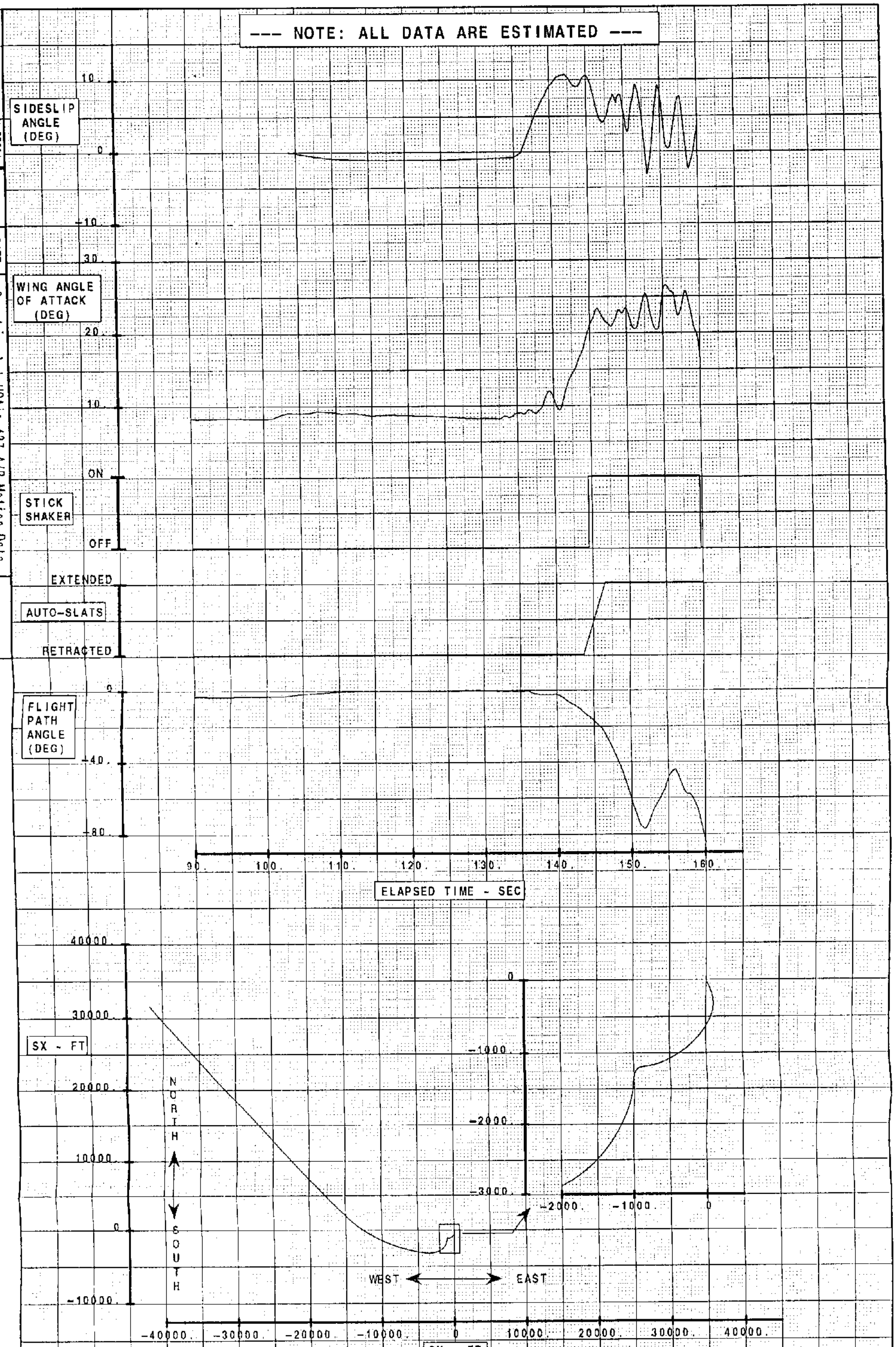

FIGURE 2

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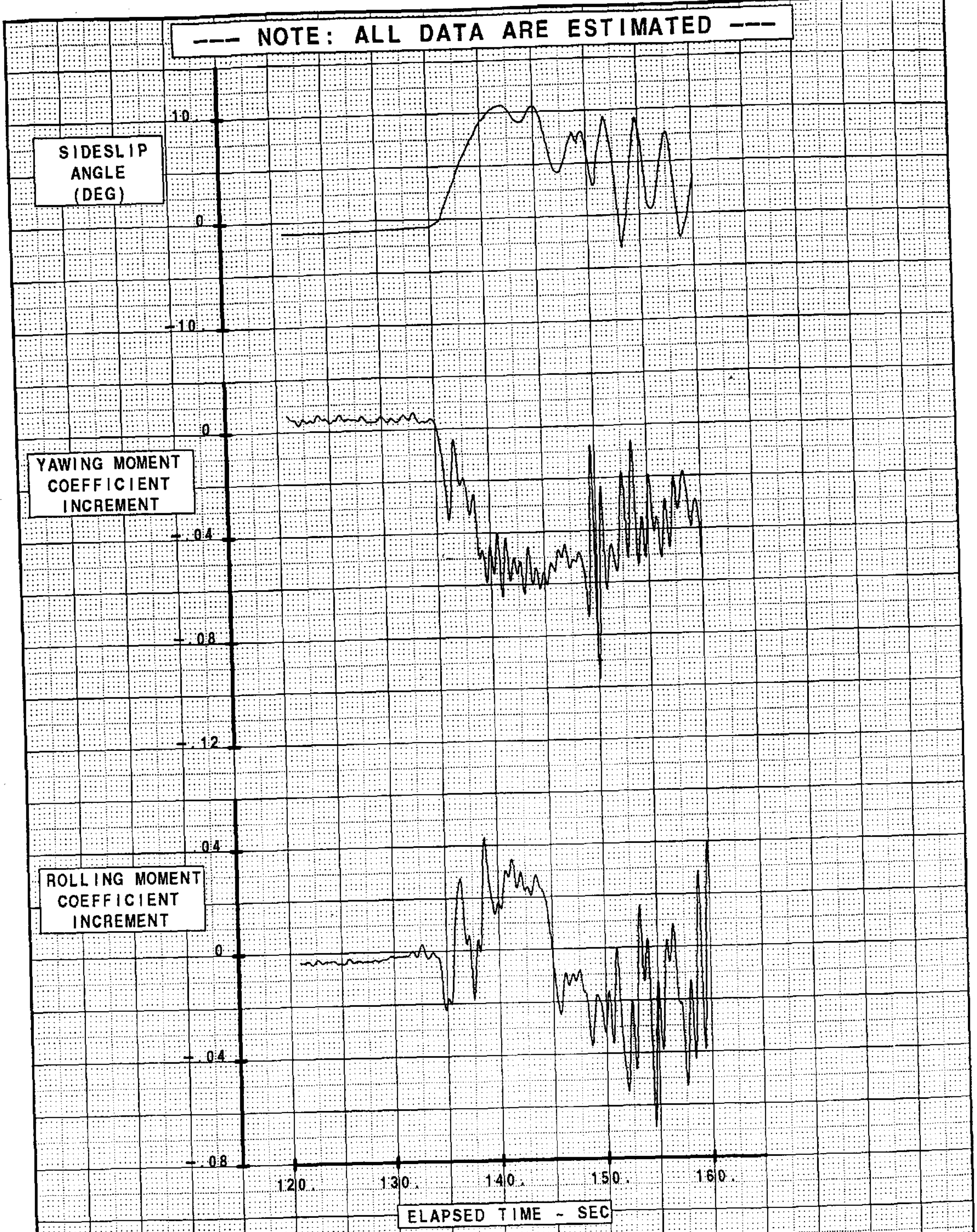

FIGURE 3

CALC	H. Dellicker	21DEC94	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Lateral/Directional -- (Rudder, Wheel and Stab set to Zero)	737-300
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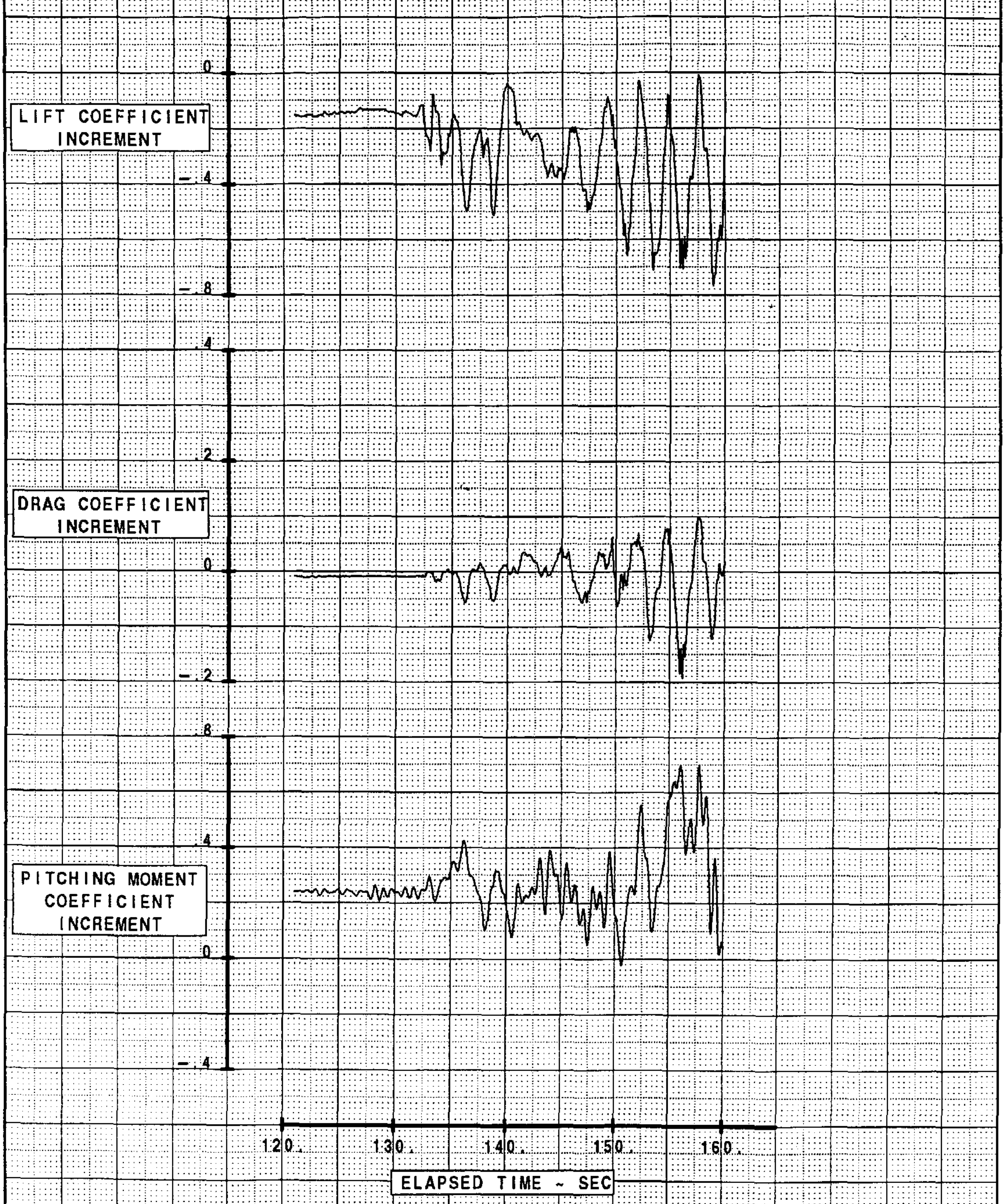

FIGURE 4

CALC	H. Dellicker	06JAN95	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Longitudinal -- (Rudder, Wheel and Stab set to Zero)	737-300
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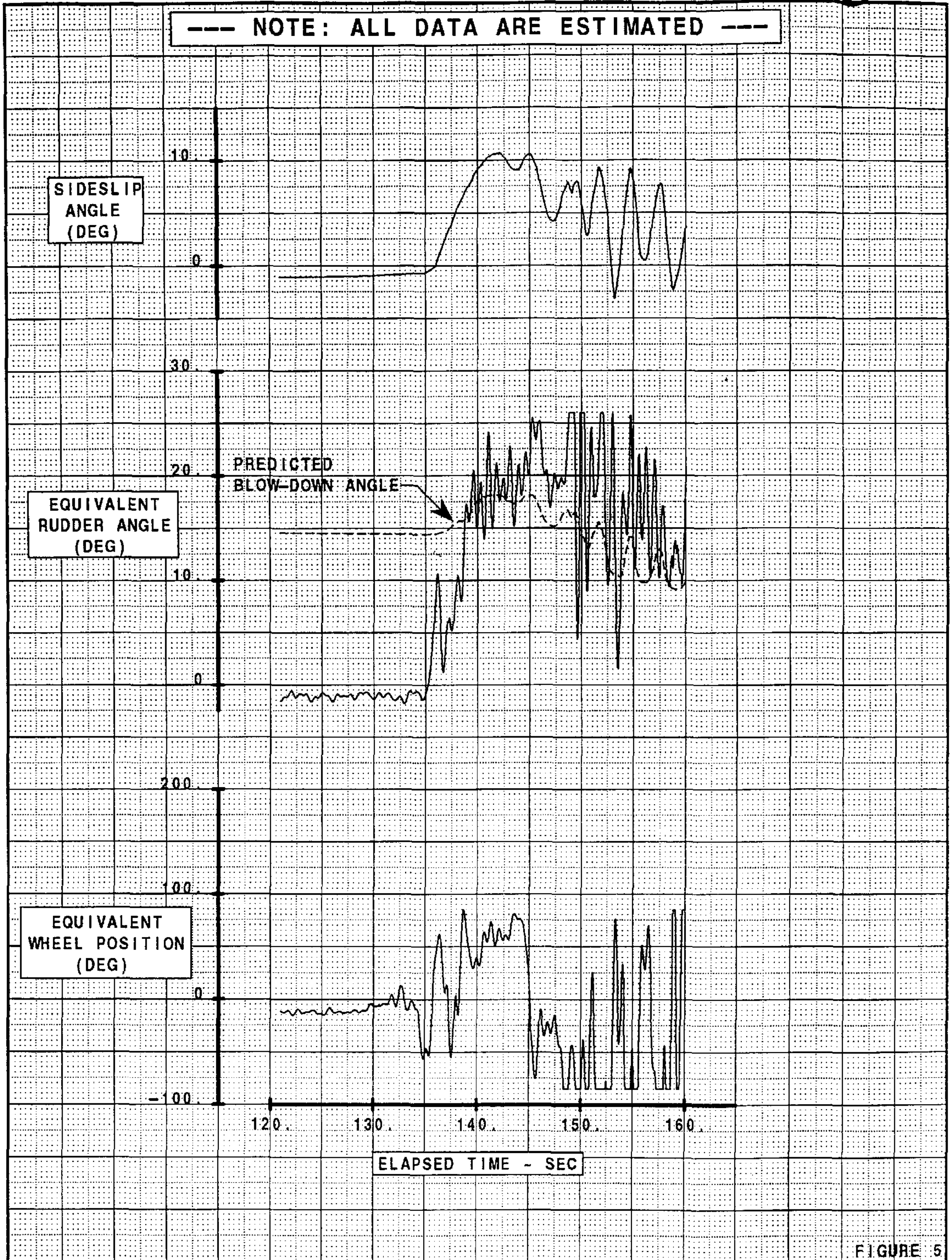

FIGURE 5

CALC	H. Dellicker	21DEC94	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Lateral/Directional -- (Yaw & Roll Trimmed with Rudder & Wheel	737-300
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--- NOTE: ALL DATA ARE ESTIMATED ---

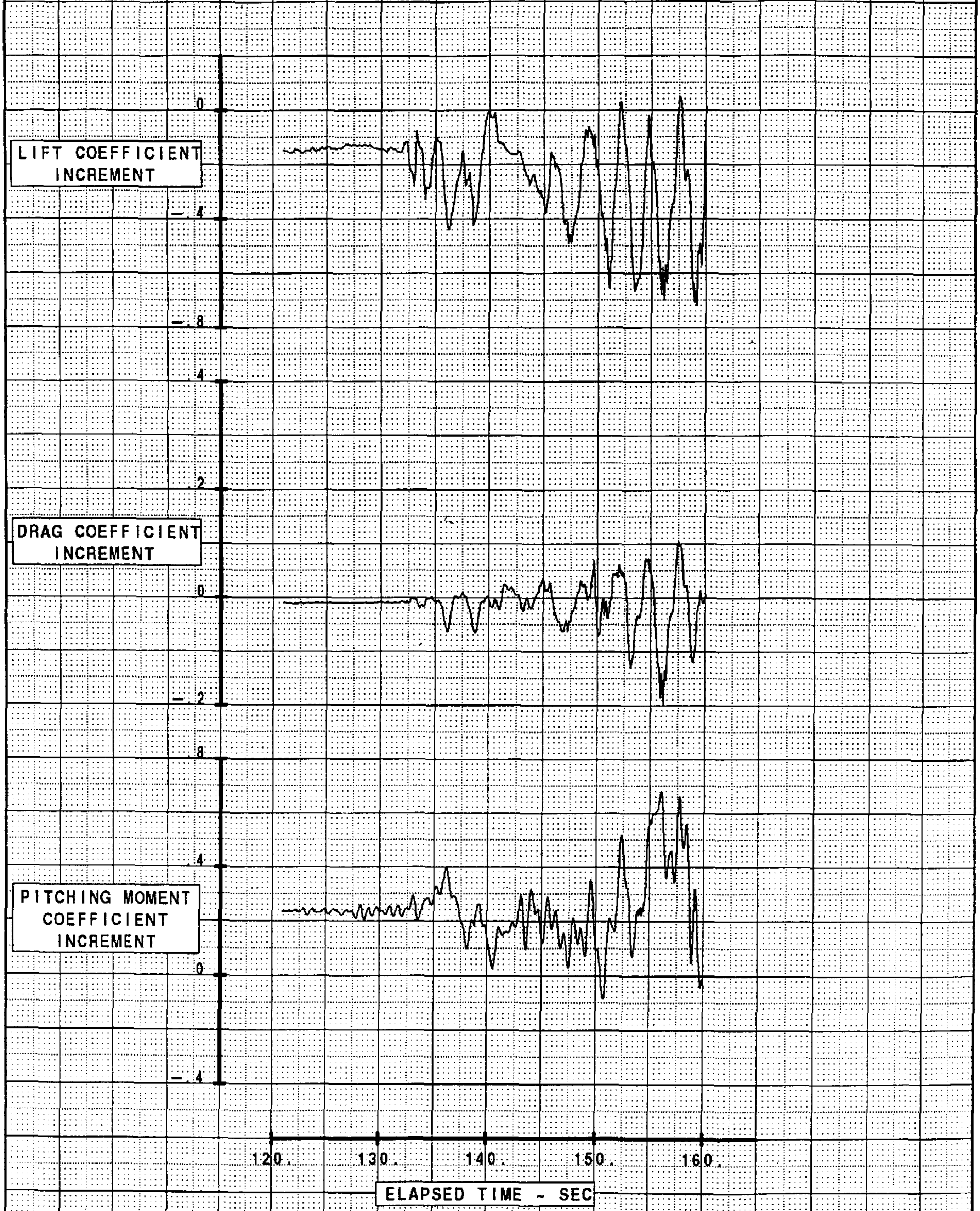

FIGURE 6

CALC	H. Dellicker	21DEC94	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Longitudinal -- (Yaw & Roll Trimmed with Rudder & Wheel)
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USAir 427 Airplane Motion Data
And Equivalent Rudder and Wheel
As Described in the Attached Report

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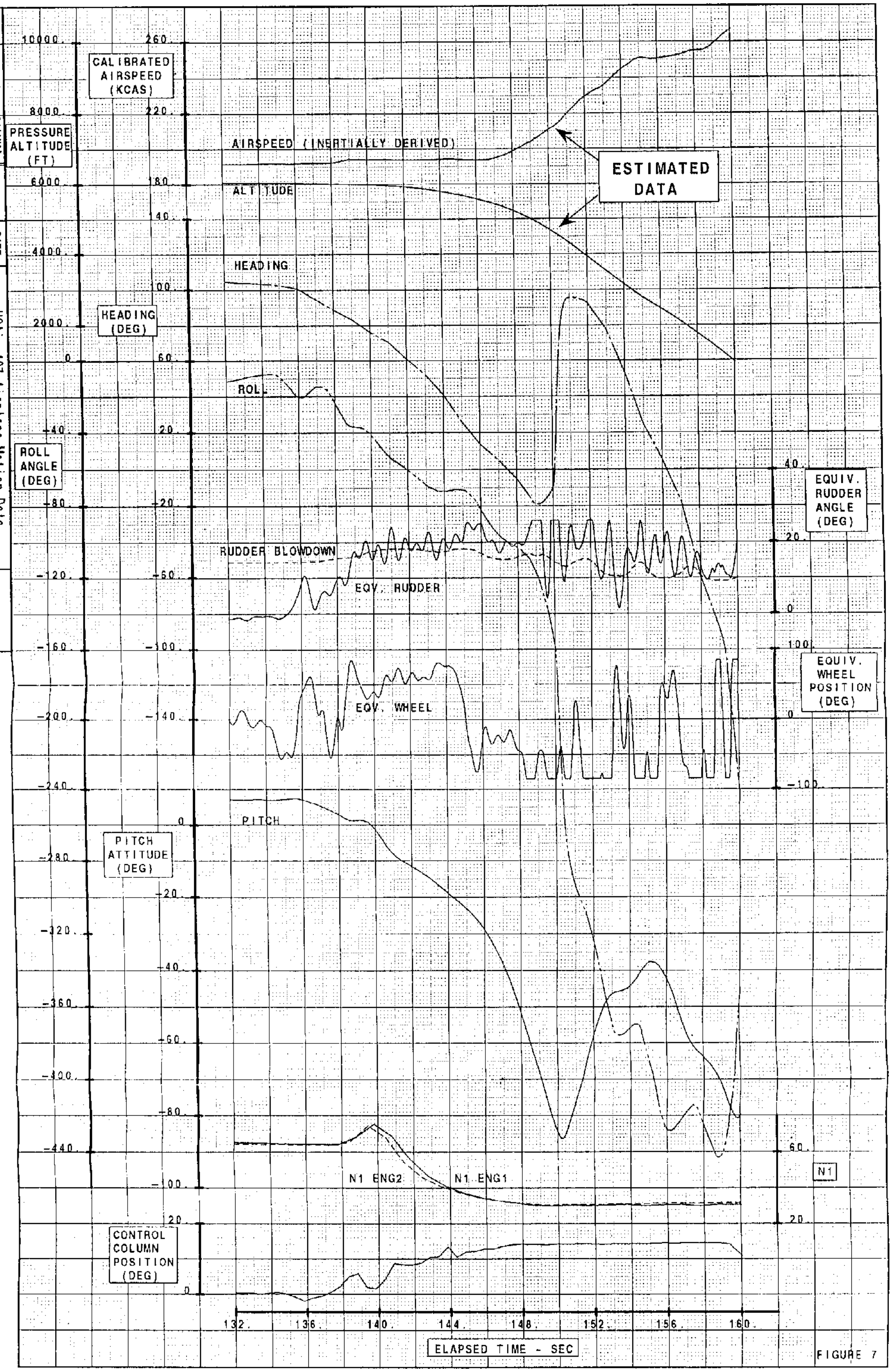

FIGURE 7

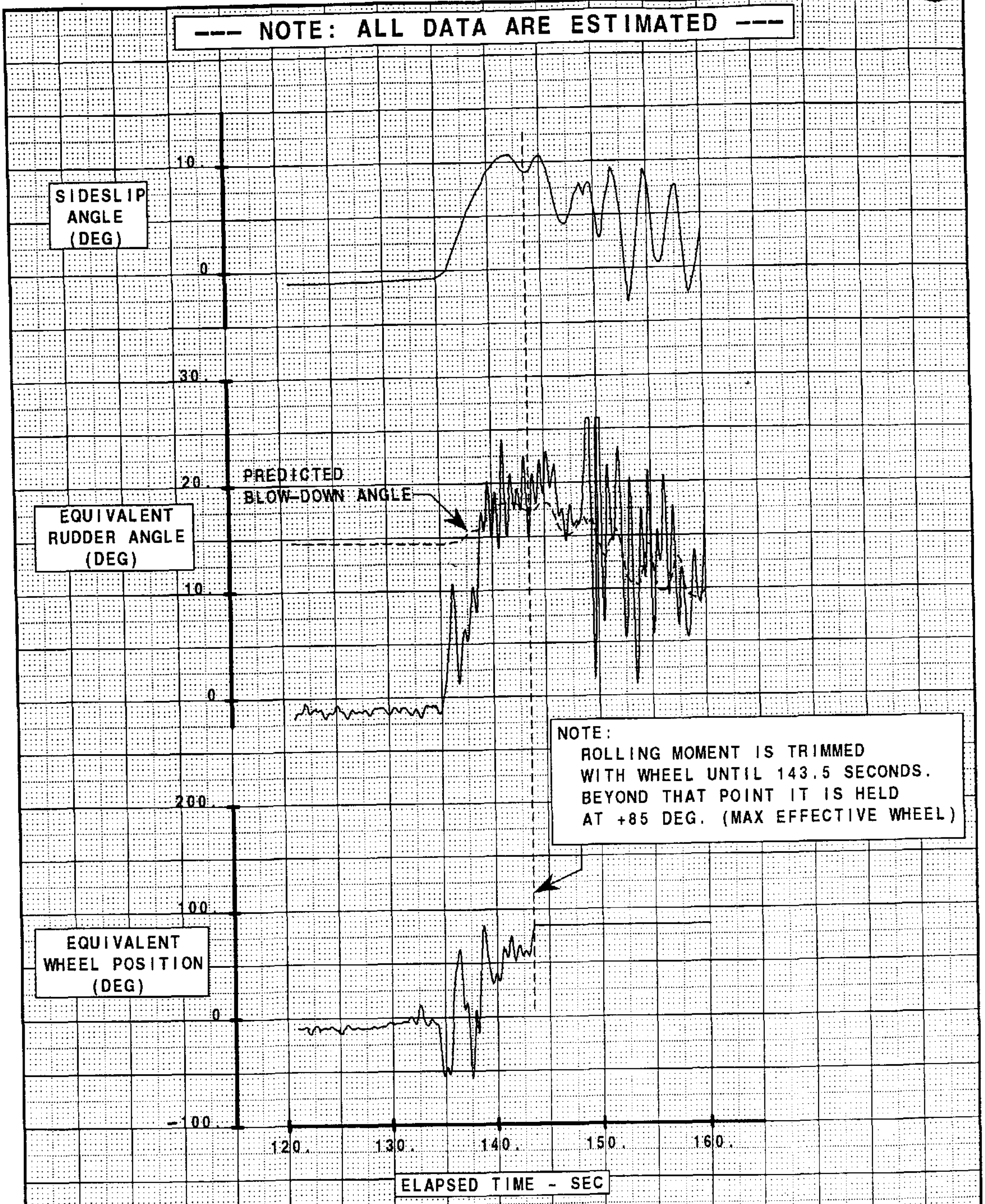

FIGURE 8

CALC	H. Dellicker	06JAN95	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Lateral/Directional -- (Yaw Trimmed w/Rudder: Roll, see Note)	737-300
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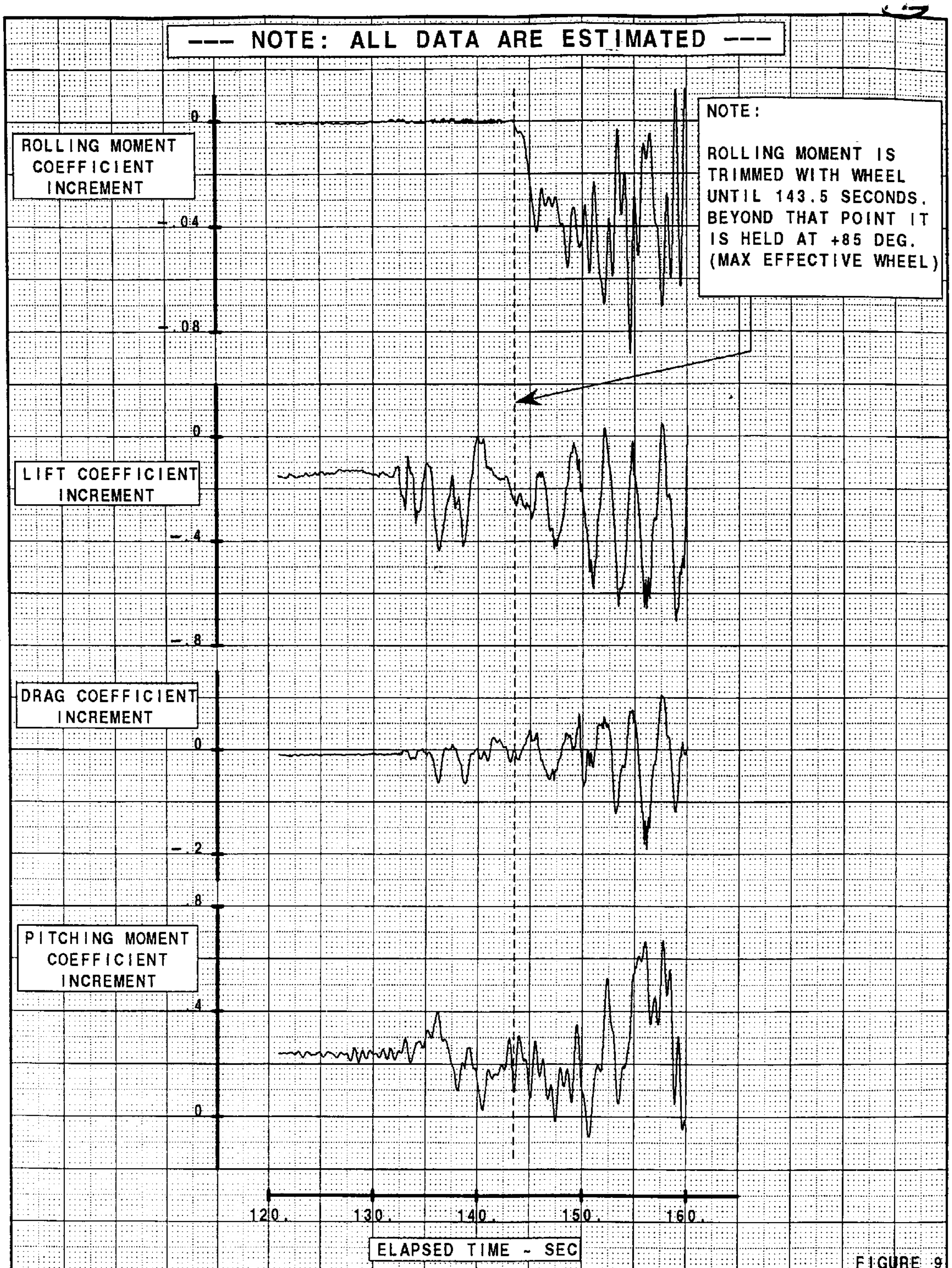

FIGURE 9

CALC	H. Dellicker	06JAN95	REVISED	DATE	USAir 427 Aerodynamic Coefficient Data -- Lateral/Directional & Longitudinal -- (Yaw Trimmed w/Rudder)	737-300
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USAir 427 Airplane Motion Data And Equivalent Rudder and Wheel Angle As Described in the Attached Report

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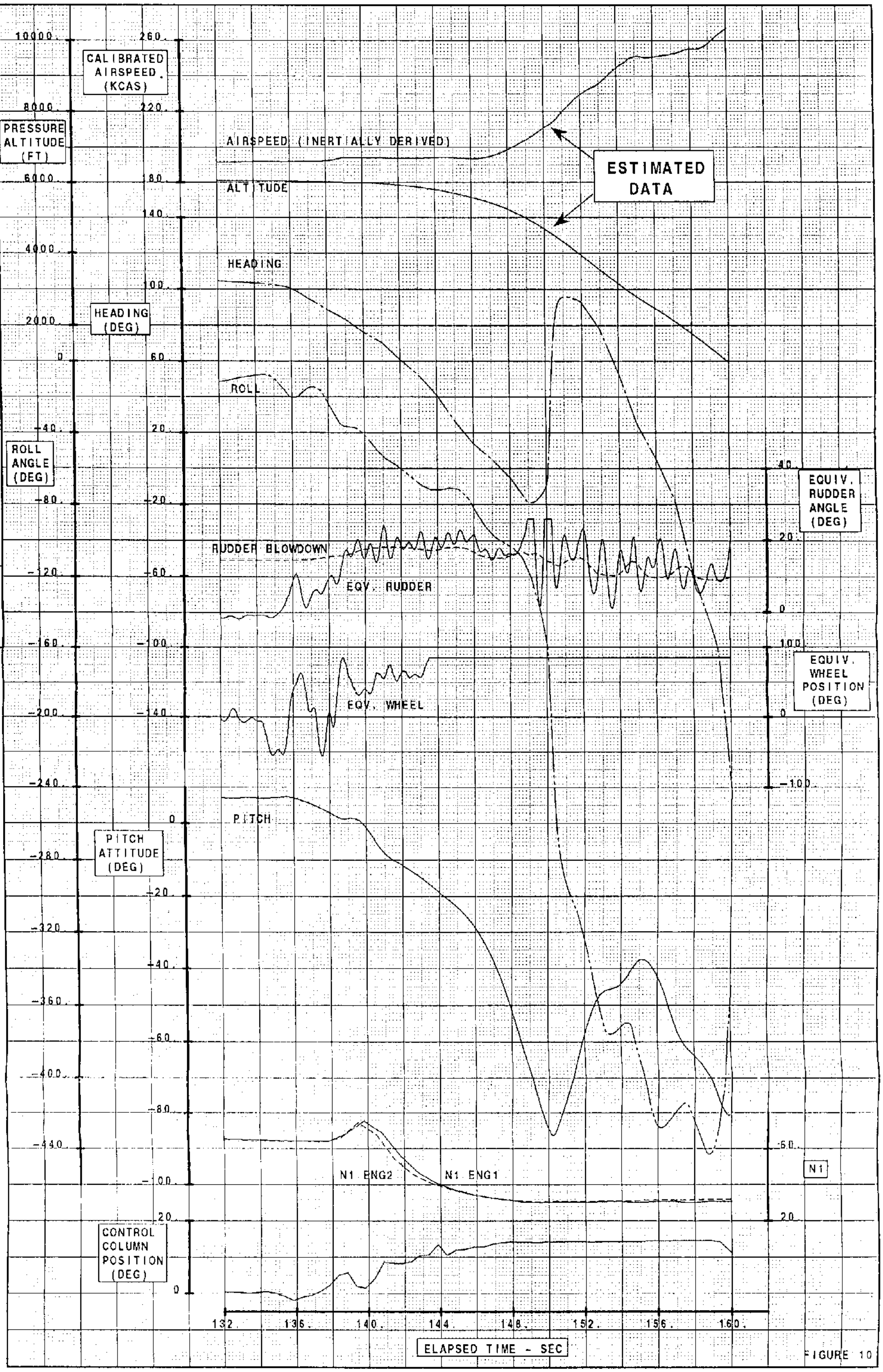

FIGURE 10

Appendix A: Description of Kinematic Analysis

Kinematics: A branch of dynamics that deals with aspects of motion apart from considerations of mass and force. (Webster's Dictionary)

Using the kinematic equations of motion, it is possible to estimate all aspects of an airplane's motion, given certain key pieces of information. In the case of USAir 427, the following information was available:

FDR Data:	Sample Rate	Transport Delay (Sec)
1. Pitch attitude	4	0.05
2. Roll angle	2	0.05
3. Heading angle	1	0.11
4. A/P body axis longitudinal acceleration (Nx)	4	0.00
5. A/P body axis vertical acceleration (Nz)	8	0.00
6. Indicated airspeed and altitude	1	0.15

Non-FDR Information:

7. Approximate winds aloft at time and location of the accident
8. Atmospheric temperature and pressure at time and location of the accident
9. Ground elevation at the impact site
10. Time at stall warning onset
11. Continuous operation of stall warning after onset (intermittent in last 3 seconds???)
12. Leading edge slats fully extended at impact
13. Impact site map showing location of airplane debris
14. Approximate airplane center of gravity
15. Transport delay times for the FDR data
16. Nominal corrections to airspeed and altitude for sideslip & angle-of-attack effects
17. Nominal alpha vane calibration curve

Early attempts to analyze these data assumed zero sideslip angle. Sideslip was not measured or recorded, and there was no reason, initially, to suspect the presence of significant sideslip. This assumption resulted, however, in estimated values for altitude, airspeed and angle-of-attack which did not match the recorded altitude, airspeed and stall warning trip point. The following process was then developed, and it was found that an approximation for sideslip could be derived which results in a set of motion parameters that agree well with the known data.

For the purposes of the following discussion, the recorded airplane motion is divided into two flight regimes:

Flight Regime 1: The first 132 seconds of stable, controlled flight
Flight Regime 2: From 132 seconds, until impact at approximately 160 seconds.

The documented FDR data and non-FDR information sources are used in the following steps to estimate the airplane motion throughout the entire 160 seconds of recorded data:

1. All relevant FDR data are corrected for the documented nominal transport delays.

2. Data Items 1, 2, 3, 6, 7 and 8 are used to estimate the body axis inertial velocities (u, v and w) in Flight Regime 1. These estimates are then used in Step 4 to calibrate the measured longitudinal and vertical accelerations.

3. Data Items 1, 2 and 3 are used to estimate the airplane body axis angular rates and accelerations (p, q, r, pdot, qdot and rdot) for the entire 160 seconds.

4. Data Items 1, 2, 3, 4, 5, 7 and 8, along with the derived values for u, v, w, p, q and r, are then used to estimate the airplane airspeed and altitude in Flight Regime 2.

   - As mentioned in Step 2, the accelerations (Data Items 4 and 5) are calibrated using the data in Flight Regime 1. These data are then used for estimating the body axis u and w velocities in Flight Regime 2.

   - The body axis v velocity, in Flight Regime 2, is derived from an assumed sideslip angle. The actual sideslip was not measured or recorded.

   - As it turns out, the derived airspeed and altitude are relatively strong functions of the assumed sideslip angle (Figure A-1), providing an excellent tool for judging the accuracy of the assumption.

   - The procedure is iterative. In each pass through the process the table of sideslip angle versus time is manually modified. This information is used to update the kinematically derived estimates of airspeed and altitude, which are then visually compared with the recorded airspeed and altitude, and the known impact elevation. Based upon the results of this comparison, the estimated sideslip is updated and the process is repeated.

5. The result of the procedure in Step 4 is a relatively smooth, low order representation of sideslip angle (Figure A-2), leaving out the high order components resulting from the oscillatory motion of the aircraft.

   - Using the kinematic relationships defining body axis lateral acceleration (Ny), along with an estimate of the maximum Ny which can be achieved (given the aerodynamic characteristics of the 737-300), it is possible to estimate the high order components of the sideslip angle (Figure A-3), ignored in Step 4. These results are then added to the original, low order estimate.

   - Step 5 is done only <u>once</u>. The high order approximation is quite good, as determined by validation with simulator data, but does not result in mathematical convergence if one attempts to iterate on it.

6. Step 4 is then repeated, as necessary, with manual adjustments to both the low order and high order estimates of sideslip. This continues until an adequate match of all the known data has been achieved.

Using these techniques, the resulting estimated altitude and airspeed match the recorded data quite well throughout Flight Regime 1. In Flight Regime 2 they generally match to within about 100 feet and 10 knots, respectively (Figures A-4 and A-5). The differences are probably due to the inability to completely account for all sideslip and angle-of-attack effects on the recorded airplane data.

Based on the derived altitude, impact is estimated to have occurred at about 160.04 seconds from the beginning of the FDR data; less than one Nz data sample (.125 seconds) beyond the end of the last Nz data point.

The estimated angle-of-attack resulting from the analysis places the onset of stall warning within about 0.2 seconds of the stall warning onset recorded on the Cockpit Voice Recorder (CVR). The predicted stall warning continues, without stopping, until about 159.7 seconds (0.3 seconds prior to impact). This has yet to be verified on the CVR.

And finally, the oscillations in the predicted sideslip angle correlate well with the observed, large amplitude oscillations in the vertical acceleration, providing a possible explanation of that phenomenon.

Assumptions and Limitations:

The kinematic analysis used in this study has proven to be very useful, providing additional insight into the USAir 427 accident, beyond what can easily be learned with the airplane simulation alone. Unfortunately, this methodology is not generally applicable to all accident investigations. The following list of assumptions and limitations may be used to determine when this technique can be applied:

- Accurate Euler angles (pitch, roll and heading) are required. Euler angles from an IRU are normally quite good (except when pitch attitude exceeds +/- 85 degrees). Heading angle measurements from the directional gyro systems on older aircraft, on the other hand, are suspect any time significant roll angles are involved. The sample rates available for this study appear to be adequate, although higher rates are desirable.

- Accurate data are required for longitudinal and vertical body axis accelerations (Nx and Nz) These data may be taken from an IRU or from dedicated accelerometers. The sample rates available for this study appear to be adequate as long as the noise level in the data is minimal (i.e. the signal to noise ratio is good). As the signal to noise ratio is degraded (as in the case of airplane buffet), the sample rate must be higher or the results of the analysis will be likewise degraded.

- Airspeed and altitude must be reasonably accurate. Corrections for known angle-of-attack and sideslip effects can be approximated, based on flight test data. Airspeed errors which can not be accounted for will degrade the results of the analysis, proportional to the size and duration of the error. The sample rates available for this study appear to be adequate.

- Winds aloft at the time and location of the accident must remain low and steady through the majority of the data set and be fairly well known. Brief excursions in measured airspeed, as in the case of wake encounters, will not significantly affect the results of the analysis. Large, unpredictable winds, however, can not be tolerated by this analysis.

- The amount of FDR data recorded during stable flight, immediately preceding the upset, should be several times as long as the segment between the upset and impact. For example, if the time between upset and impact is 30 seconds, the time from the beginning of data until the upset should be about 2 minutes.

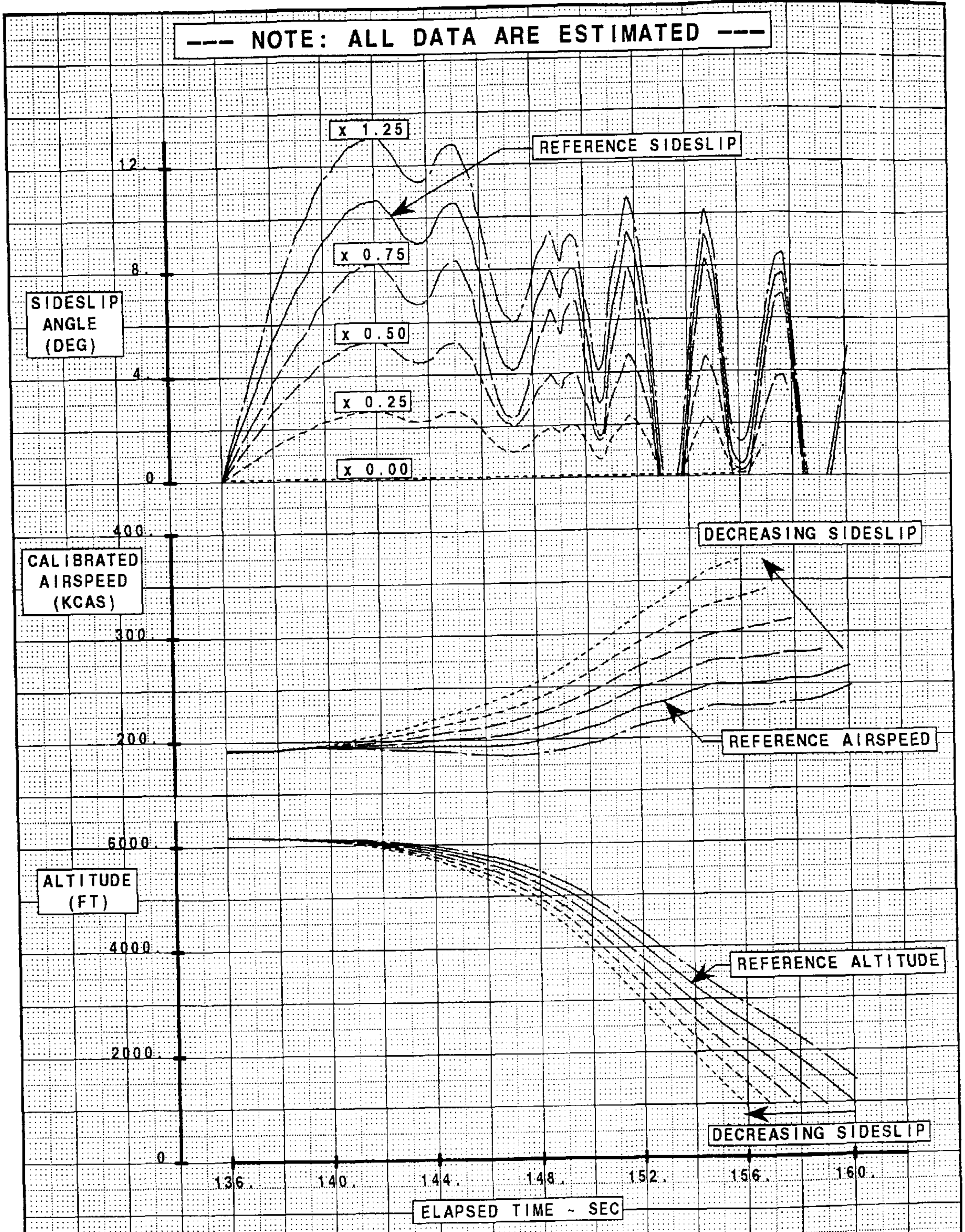

FIGURE A-1

CALC	H. Dellicker	06JAN95	REVISED	DATE	Effect of Sideslip Angle on Kinematic Solution for Airspeed and Altitude	737-300
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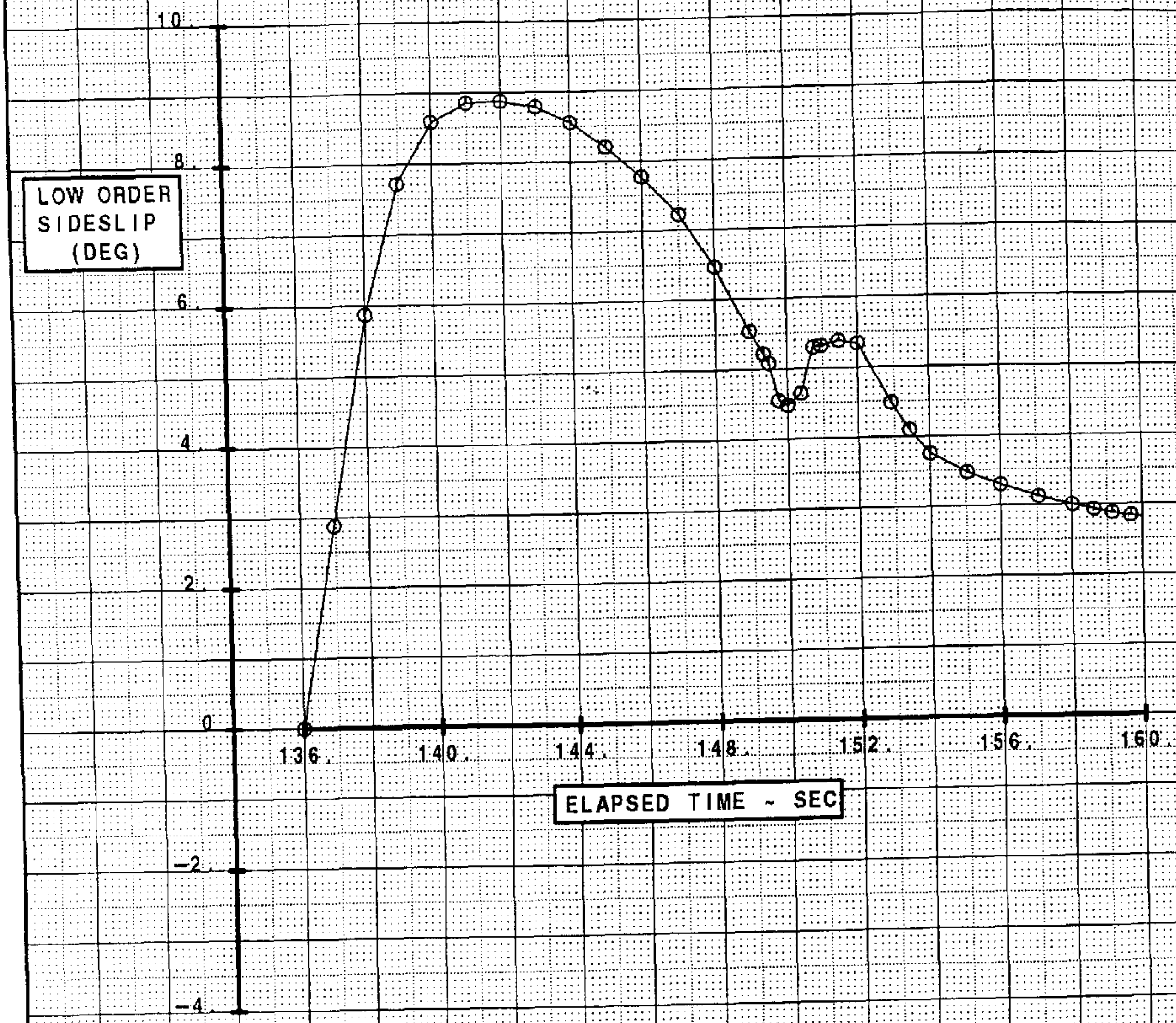

FIGURE A-2

CALC	H. Dellicker	12/22/94	REVISED	DATE	USAir 427 Low Order Estimated Sideslip Angle	737-300
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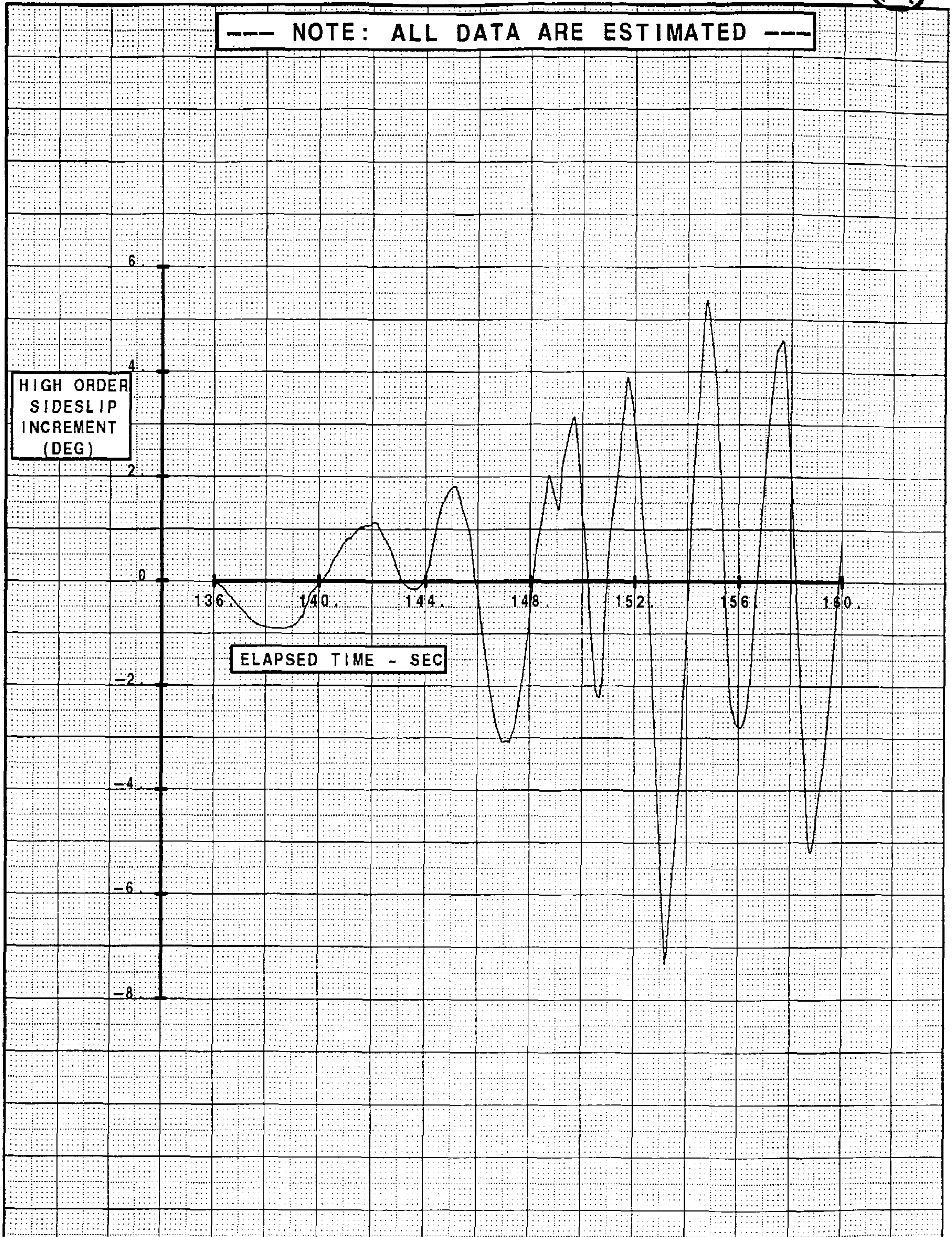

FIGURE A-3

CALC	H. Dellicker	12/22/94	REVISED	DATE	USAir 427 High Order Estimated Sideslip Angle Increment
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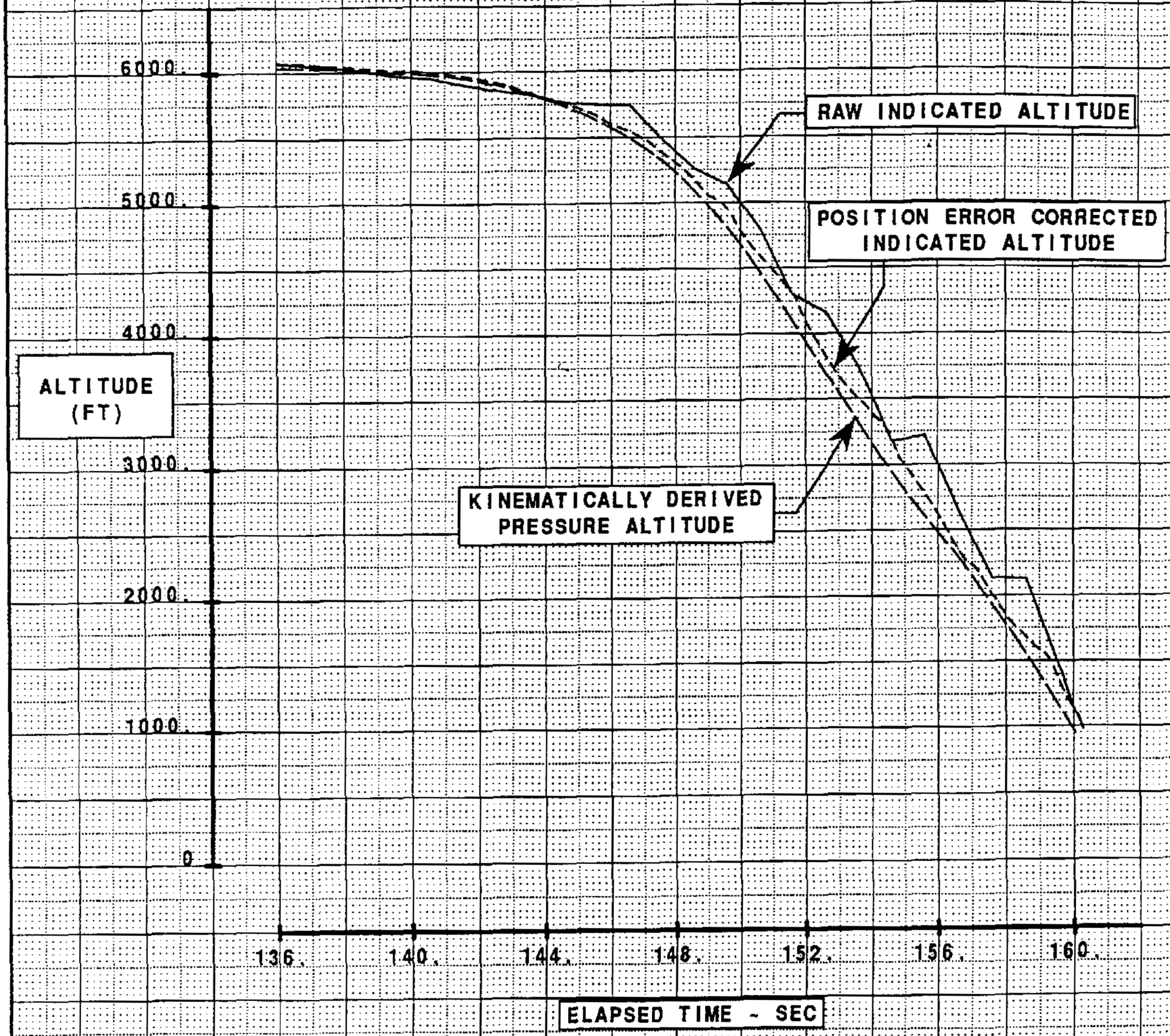

FIGURE A-4

CALC	H. Dellicker	04JAN95	REVISED	DATE	Comparison of Raw Indicated Altitude vs Corrected Altitude	737-300
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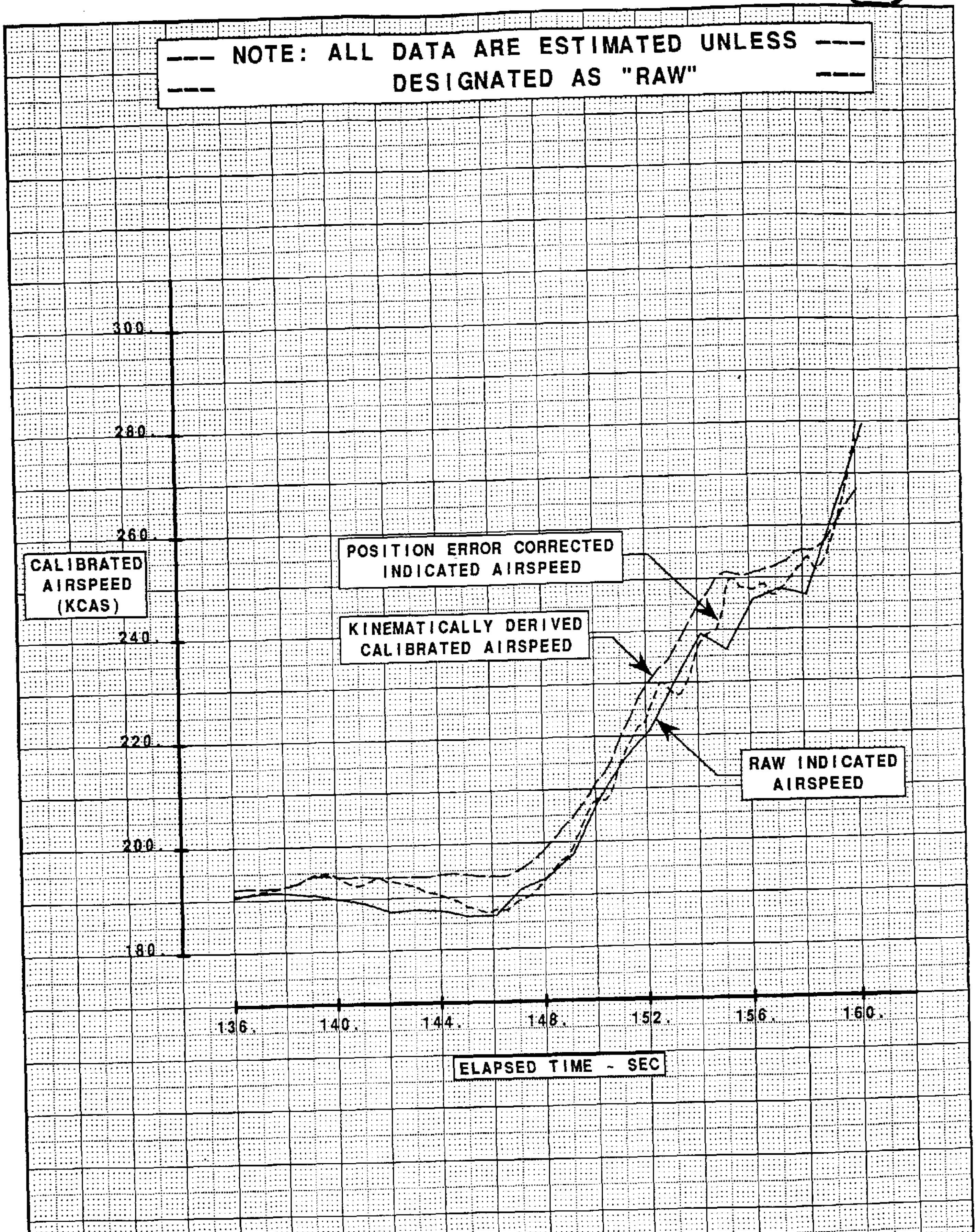

FIGURE A-5

CALC	H. Dellicker	04JAN95	REVISED	DATE	Comparison of Raw Indicated Airspeed vs Corrected Airspeed	737-300
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Appendix B: Computer Code and Data Used in the Kinematic Analysis

This appendix includes a listing of the computer code used in the USAir 427 accident investigation, followed by plots of the referenced data tables required by the program.

APPENDIX B IS CONSIDERED PROPRIETY AND IS WITHHELD.

Appendix C: Description of Aerodynamic Coefficient Analysis

Reference: D6-37908, "Aerodynamic Data and Control System Description for the 737-300 Flight Simulator", Rev C, January 30, 1992

Given a set of flight data containing airplane configuration, weight, center of gravity and inertias, along with the full set of motion data, it is possible to estimate the total forces and moments acting on an aircraft at each point in time, and to relate that information to the forces and moments predicted by the simulation model.

The procedure is as follows:

1. Calculate dynamic pressure:

   - Qbar = (Ve**2) / 295.37

2. Calculate coefficient non-dimensionalizers:

   - QbS/W = Qbar * (Wing Ref. Area) / Weight
   - QbSC = Qbar * (Wing Ref. Area) * (Wing Chord)
   - QbSS = Qbar * (Wing Ref. Area) * (Wing Span)

3. Calculate the airplane body axis force and moment coefficients, at the cg, required to match the airplane motion:

   - Cx = Nxcg / (QbS/W)
   - Cy = Nycg / (QbS/W)
   - Cz = Nzcg / (QbS/W)

   - Cm = [Qdot*Iyy - (Izz - Ixx)*P*R - (R*R - P*P)*Ixz] / QbSC
   - Cn = [Rdot*Izz - (Pdot - Q*R)*Ixz + (Iyy - Ixx)*P*Q] / QbSS
   - Cr = [Pdot*Ixx - (Rdot + P*Q)*Ixz + (Izz - Iyy)*Q*R] / QbSS

4. Convert the results of Step 3 to stability axis coefficients ("alw" is wing angle of attack):

   - C_L = Cx * sin(alw) - Cz * cos(alw)
   - C_M = Cm
   - C_D = - Cx * cos(alw) - Cz * sin(alw)

   - C_R = Cr * cos(alw) + Cn * sin(alw)
   - C_N = Cn * cos(alw) - Cr * sin(alw)
   - C_Y = Cy

5. Calculate the predicted stability axis force and moment coefficients, at the cg, using the referenced simulator aerodynamic model. This process uses the airplane configuration and motion data as inputs. It is independent of weight and inertias.

6. Subtract the results of Step 5 from Step 4. This results in a set of incremental coefficients which represent what would have to be added to the simulation aero model to enable it to match the airplane motion.

7. As an alternative to the pure coefficient analysis in Step 6, it is also possible to represent selected coefficients (e.g. C_N and C_R) as equivalent control surface deflections. When this is done, all aerodynamic effects of each surface are accounted for. For example, the rudder is used to trim C_N, but it also influences rolling moment and, therefore, the estimated control wheel position. Likewise, the wheel to trim C_R influences the estimated rudder deflection.

737-300 Simulation Match of USAir 427 FDR Data

References: 1. NTSB letter, "USAir Flight 427 accident at Aliquippa, Pennsylvania, 9/8/1994, to Mr. Rick Howes from Tom Jacky, dated December 1, 1994

2. D6-37908, "Aerodynamic Data and Control System Description for the 737-300 Flight Simulator", Rev. C, January 30, 1992

Summary

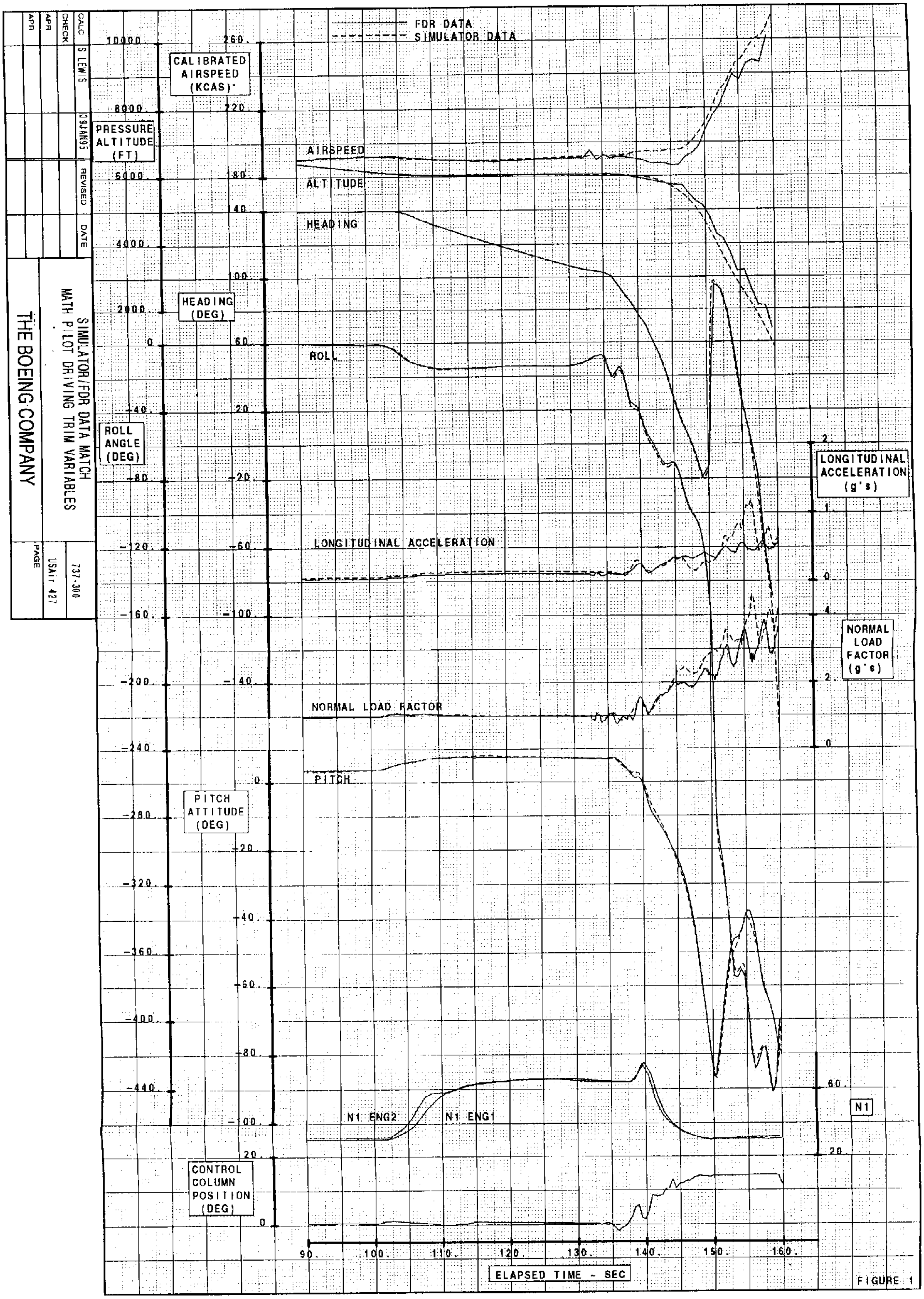
The reference 1 letter requested the most recent iteration of the backdrive effort of the USAir 427 flight data recorder (FDR) data. Figures 1 through 6 provide that information. The process used to determine these data and an explanation of the differences between these figures and those previously supplied is provided in the following paragraphs.

Discussion

The 737-300 engineering simulator (reference 2) was used to extract the aerodynamic coefficients required to match the time histories of parameters from the USAir 427 FDR. Parameters from the FDR were differentiated to determine the angular rates that the accident aircraft experienced. The simulator was then driven via arbitrary aerodynamic coefficients to reproduce as closely as possible the FDR traces. The match obtained is shown in figures 1 and 2 (different time scales).

Figures 3 and 4 show the aerodynamic coefficients required to obtain the match and also show the sideslip angle and wing angle of attack that result. Figures 5 and 6 show the wheel, rudder and column angles equivalent to the aerodynamic coefficients shown in figures 3 and 4. The values for rudder and wheel shown in this plot were not recorded on the FDR and do not represent known or suspected pilot or control system input to the airplane. These values represent the summation of all moments applied to the aircraft, including external moments, control inputs and any system or structural damage which may have occurred. These values are shown only to provide a feel for the level of upset required to produce the flight path experienced by the USAir 427 aircraft.

The differences between these figures and those previously supplied are primarily a result of a change to the process used to calculate the match, an improved method of deriving angular rates from the FDR parameters, and a better understanding of how to handle the mathematical singularity that occurs when pitch angle goes through ~ -90°. The change to the process was that the simulation is now driven with aerodynamic coefficients directly, instead of driving through the control system and that airspeed and altitude are now being driven to kinematically corrected values instead of the raw FDR data.


FDR DATA
SIMULATOR DATA
CALIBRATED AIRSPEED (KCAS)
PRESSURE ALTITUDE (FT)
HEADING (DEG)
ROLL ANGLE (DEG)
PITCH ATTITUDE (DEG)
CONTROL COLUMN POSITION (DEG)
LONGITUDINAL ACCELERATION (g's)
NORMAL LOAD FACTOR (g's)
N1
AIRSPEED
ALTITUDE
HEADING
ROLL
LONGITUDINAL ACCELERATION
NORMAL LOAD FACTOR
PITCH
N1 ENG2
N1 ENG1
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MATH PILOT DRIVING TRIM VARIABLES
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SIMULATOR/FDR DATA MATCH
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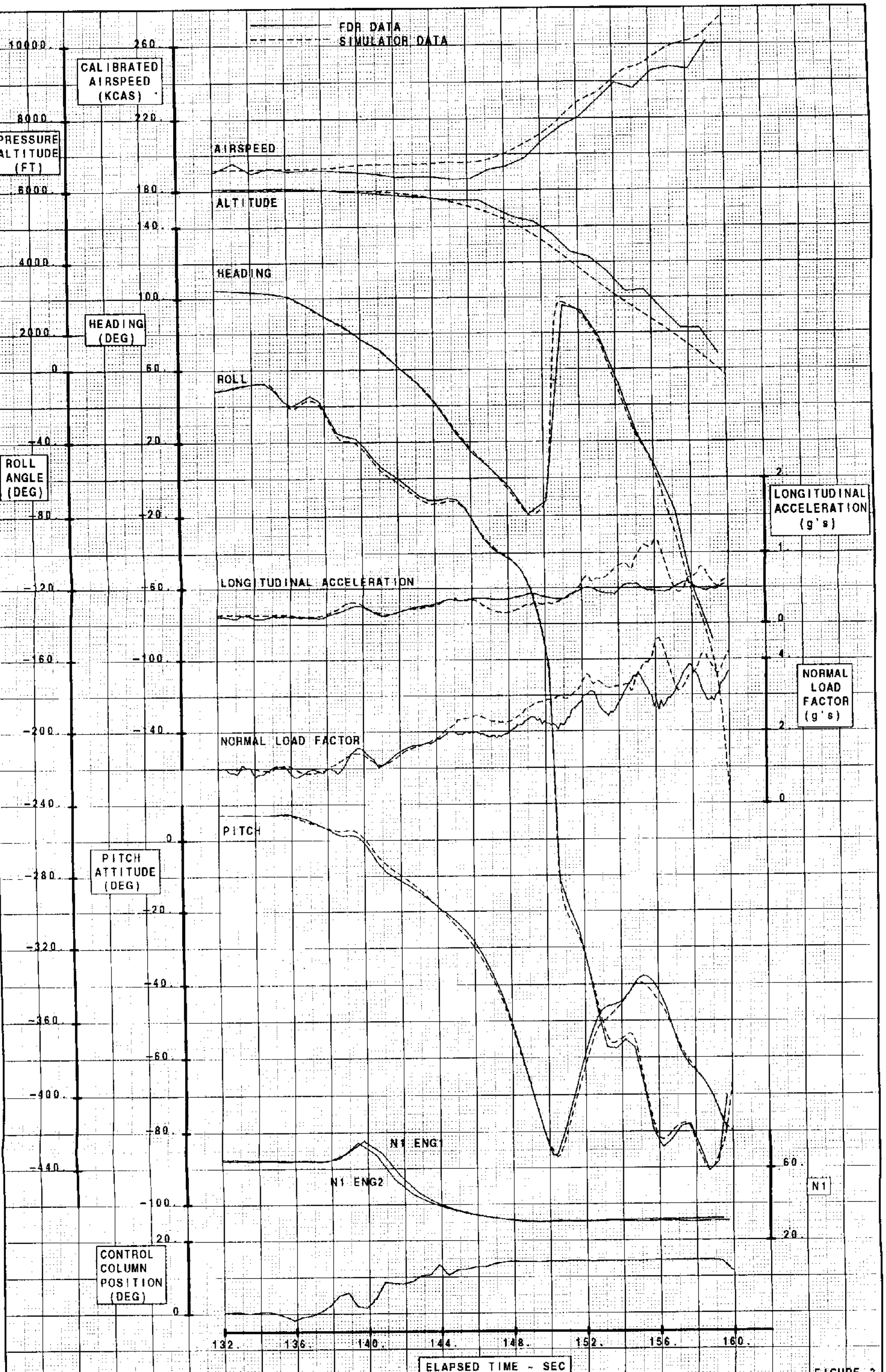

FIGURE 2

27

CALC S LEWIS 03JAN95

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DATE

SIMULATOR/FDR DATA MATCH
MATH PILOT DRIVING TRIM VARIABLES

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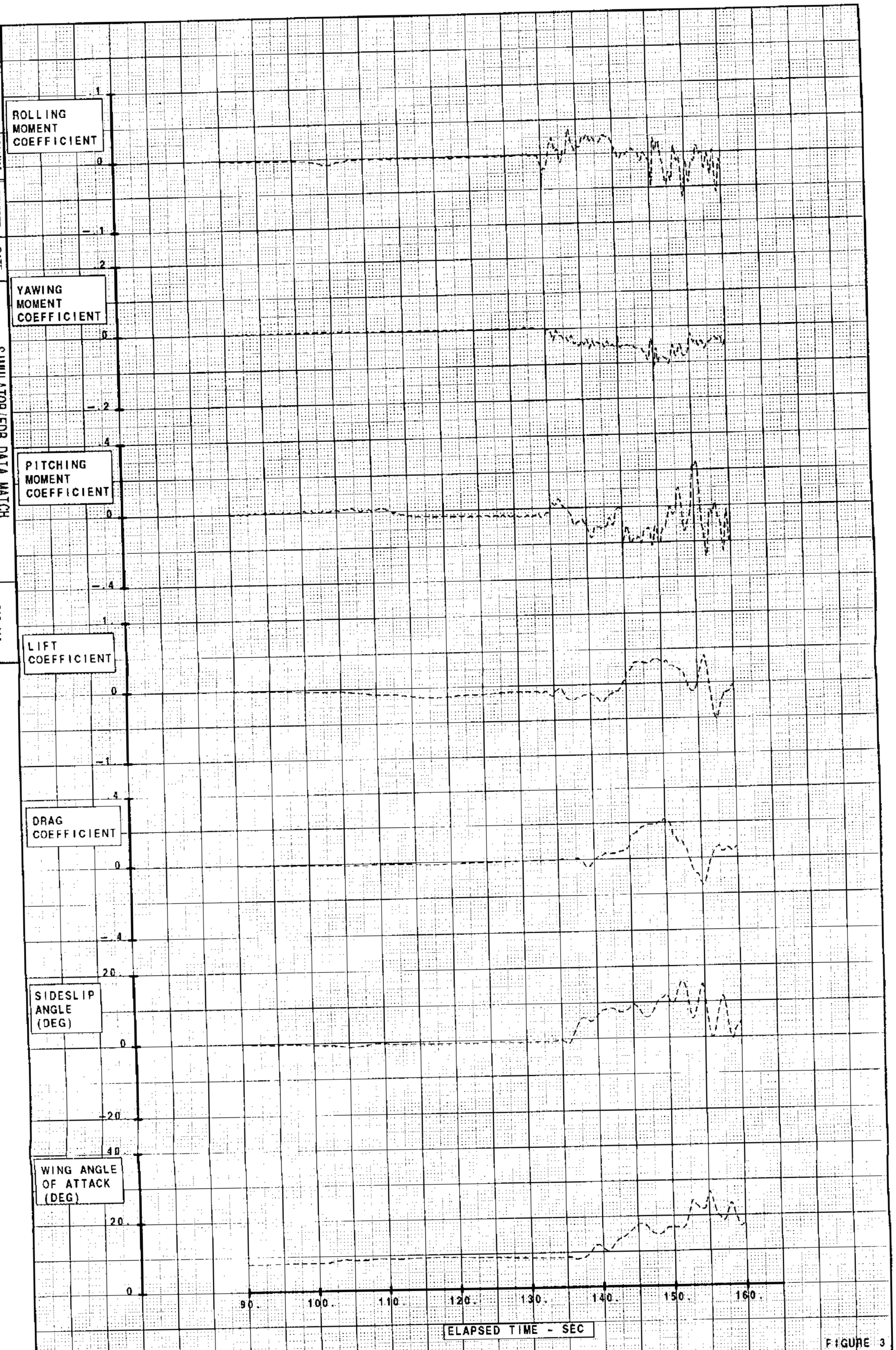

FIGURE 3

28

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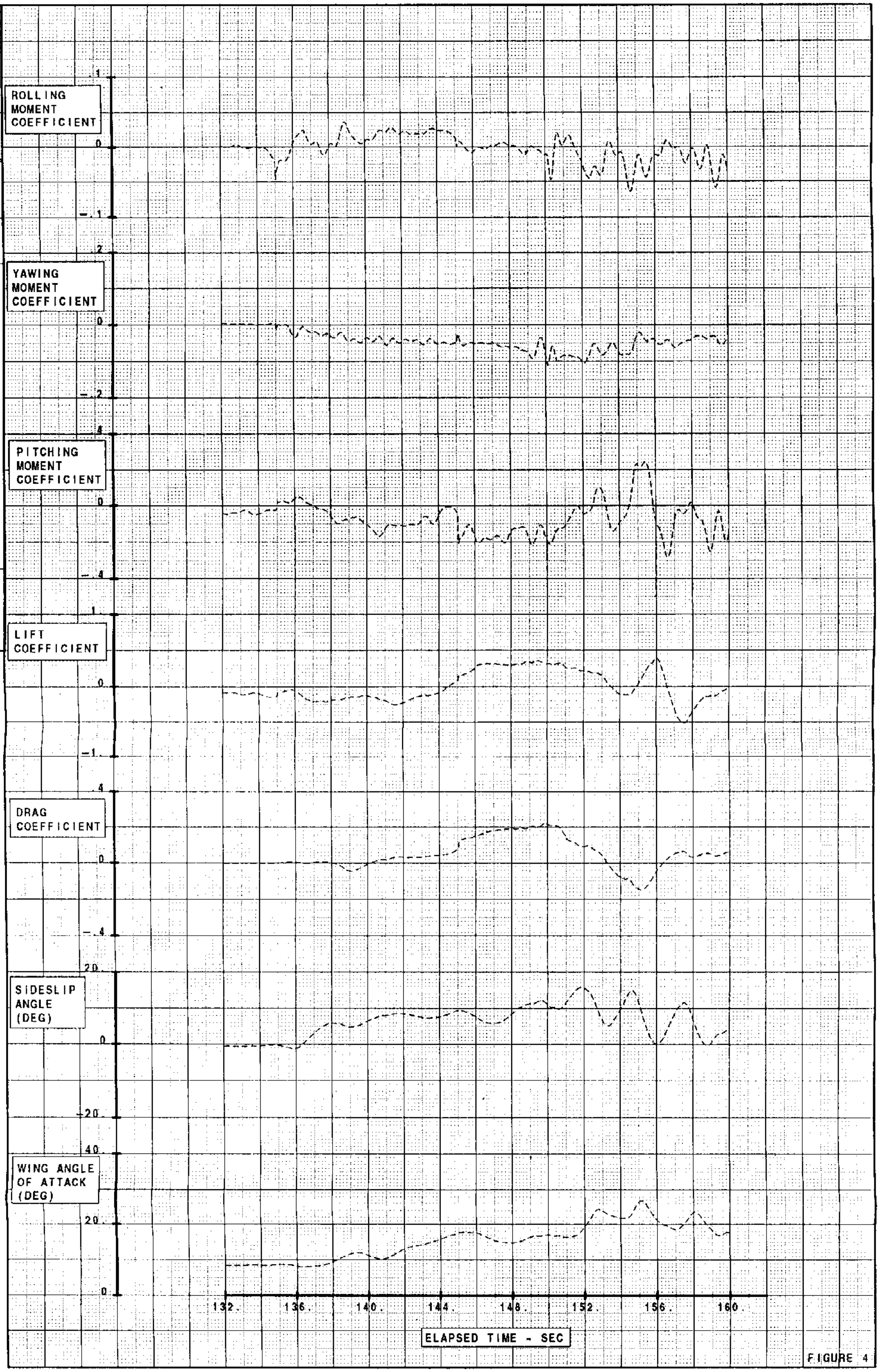

FIGURE 4

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MATH PILOT DRIVING TRIM VARIABLES

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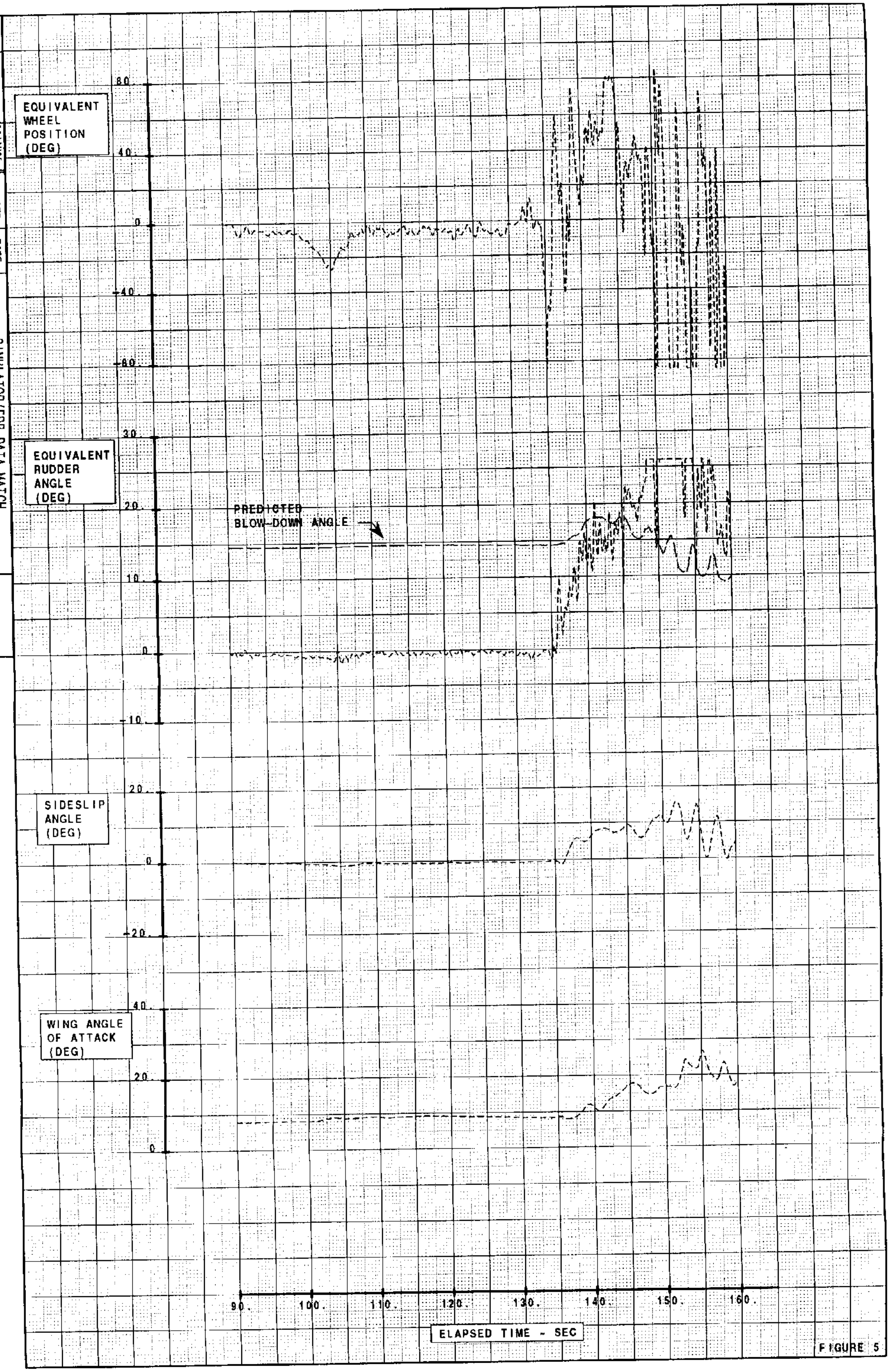
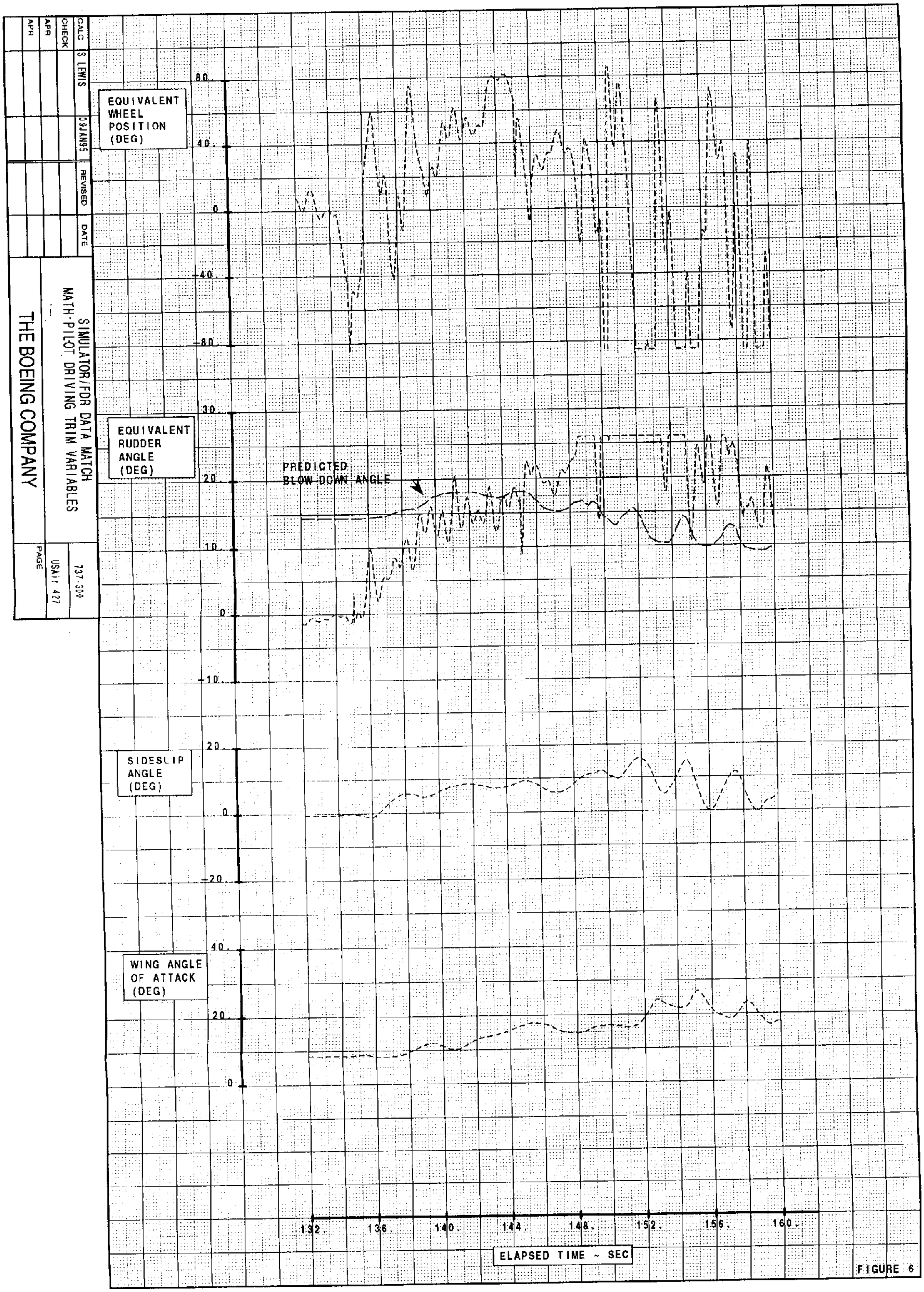


FIGURE 5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DATE
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PAGE
EQUIVALENT WHEEL POSITION (DEG)
80.
40.
0.
-40.
-80.
EQUIVALENT RUDDER ANGLE (DEG)
30.
20.
10.
0.
-10.
PREDICTED BLOW-DOWN ANGLE
SIDESLIP ANGLE (DEG)
20.
0.
-20.
WING ANGLE OF ATTACK (DEG)
40.
20.
0.
132.
136.
140.
144.
148.
152.
156.
160.
ELAPSED TIME ~ SEC
FIGURE 6