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Seattle, WA 98124-2207

October 29, 1996
B-B600-15832-ASI

Mr. Tom Jacky, RE-60
National Transportation Safety Board
490 L'Enfant Plaza SW
Washington D.C. 20594

BY FAXIMILE: 202 314-6597

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Subject: Questions Raised During the USAir Joint Performance/Systems Group Meeting at Boeing the week of September 19, 1996. USAir 737-300 Accident, N513AU near Pittsburgh, September 8, 1994

Reference B-B600- 15828-ASI, dated October 25, 1996, "Derivation of Lateral and Directional Control Positions for the USAir 427 Accident."

Dear Mr. Jacky:

The Performance and Systems Groups for the USAir 427 accident investigation along with other representatives from the NTSB and the FAA met in Seattle on September 17-19, 1996. During the meeting on September 19, a number of questions about the analysis of the wake encounter and derivation of the lateral and directional control positions were raised. The enclosure provides the information requested at the meeting.

If you have any questions, please contact me.

Very truly yours,

[redacted]

for John W. Purvis
Director, Air Safety Investigation
Org. B-B600, Mail Stop 67-PR
Telex 32-9430, STA DIR PURVIS
[redacted]

Enclosure: 18 sheets as noted

cc: Tom Haueter, AS-10
Keakini Kaulia- ALPA
Bob McCullough- USAir
Steve O'Neal- FAA

[redacted]

Introduction

During the course of the joint Performance / Systems Groups meetings for the USAir 427 accident held in Seattle held from September 16-19, 1996, the following information was requested by members of the investigation parties.

1. Describe the revised wake model used to calculate wake-induced yawing moment.
2. Provide a list of the flight test conditions used to define the revised model of wake-induced yawing moment.
3. Verify that the wake effects experienced by the empennage are correctly time-lagged relative to the wake effects experienced by the wing.
4. Provide a mapping of wake-induced pitching moment to wake-induced yawing moment.
5. Provide the value for stabilizer setting required to trim before the accident sequence, and compare to the trim setting at impact.
6. Provide the gains for the autopilot.
7. Produce a time history of the free response (no control inputs) of a 737-300 to the derived wake encounter time history.
8. Provide data comparing the crossover speed characteristics of the 737-300 simulation using the last published revision of the aerodynamic data to those using the updated aerodynamic data from the Atlantic City flight test.
9. Calculate the crossover speed characteristics of the 737-300 in a steady 30° level flight turn (load factor effect).
10. Develop a computer animation video of the USAir 427 accident with a overhead perspective of the wake encounter.
11. Provide an additional USAir 427 accident time history comparison of a 4 second rudder ramp starting at time 135.5 with the FDR data.

The information requested is provided in the following section.

Discussion

1. Describe the revised model used to calculate wake-induced yawing moment.

The modeling of wake-induced yawing moment in the wake encounter simulation was updated based upon the Atlantic City flight testing of wake encounter characteristics for the 737. This model replaced the theory-based distributed lift vertical tail model developed originally, and is an improvement because it better captures the wake-induced yawing moment characteristics measured in flight test. The model was developed by observing video footage of the wake encounters and correlating wake yawing moment (derived from measured kinematic data) with the location of the wake core relative to the vertical tail.

The model was implemented as follows: The total wake yawing moment is the product of two functions, which are implemented in the simulation as standard FDHS table look-ups. The first function, denoted CN_{WKFTD}, is the wake yawing moment as a function of normalized lateral location in the wake axes system and wake circulation strength:

$$CN_{WKFTD} = f(ynorm_w, \Gamma)$$

where $ynorm_w$ = Normalized lateral position in wake axes system
= y_w / b_{wake}
y_w = Lateral location in wake axes system (ft)
b_{wake} = Distance between wake cores (ft)
Γ = Wake circulation strength, (ft^2/sec)

The second function, KN_{WKFTD}, is a shaping factor and is a function of normalized vertical location in the wake axes system:

$$KN_{WKFTD} = f(znorm_w)$$

where $znorm_w$ = Normalized vertical position in wake axes system
= z_w / b_{wake}
z_w = Vertical location in wake axes system (ft)

It is this factor which is used to apply interference effects of the airplane on the wake flow field. Thus the total wake yawing moment, CN_{WAKE}, is calculated as

$$CN_{WAKE} = CN_{WKFTD} * KN_{WKFTD}$$

The data for the functions CN_{WKFTD} and KN_{WKFTD} are presented in Figures 1 and 2, respectively.

2. List the flight test conditions used to define the revised model of wake-induced yawing moment.

The conditions used to define the revised wake-induced yawing moment model are listed in Table 1.

3. Verify that the wake effects experienced by the empennage are correctly time-lagged relative to the wake effects experienced by the wing.

Figure 3 presents the vertical wake location relative to the wing and tail versus time. The time-lagging can be noted especially during time segment 130-135, when no wake perturbation due to aircraft flow field effects are applied. The expected time lag can be computed as

$$\Delta t = \Delta x / V_T$$

where Δt = time lag (sec)
Δx = distance from C.G. to tail MAC (ft)
V_T = aircraft true airspeed (ft / sec)

For the 737-300 traveling at 190 KCAS and at 6000 ft pressure altitude (350 ft / sec true airspeed) the time lag is 0.13 seconds. Examination of Figure 3 shows that this time lag is correctly reflected in the analysis.

4. Provide a mapping of wake-induced pitching moment to wake-induced yawing moment.

Given a set of wake characteristics (strength, span, core radius, etc.), all wake-induced effects at a given point in space are functions of two variables - the lateral and vertical location of the point in the wake axes system. Thus, a direct mapping of one wake-induced effect to another is not possible, as the function for the effect cannot be directly inverted. However, a locus of solutions can be generated for different values of one of the independent variables. Mathematically this is done as follows:

Starting with

$$C_{m_{wake}} = f_1(y_{wake}, z_{wake})$$
$$C_{n_{wake}} = f_2(y_{wake}, z_{wake})$$

where $C_{m_{wake}}$ = Wake-induced pitching moment coefficient
$C_{n_{wake}}$ = Wake-induced yawing moment coefficient
y_{wake} = Lateral location in wake axes system (ft)
z_{wake} = Vertical location in wake axes system (ft),

solve for one of the independents:

$$y_{wake} = f_1^{-1}(z_{wake}, C_{m_{wake}})$$
$$y_{wake} = f_2^{-1}(z_{wake}, C_{n_{wake}}).$$

Then, by the equivalence of the functions, set

$$f_Z^{-1}(z_{wake}, C_{nwake}) = f_Y^{-1}(z_{wake}, C_{mwake}).$$

Thus, by holding z_{wake} constant, a direct mapping function from C_{mwake} to C_{nwake} can be generated by sweeping laterally across the wake at the height corresponding to that value of z_{wake}. A locus of solutions can then be generated for a range of z_{wake} values.

This locus of solutions mapping wake-induced pitching moment to wake-induced yawing moment at the wake circulation estimated for the USAir 427 accident and a wake width of 70 feet is provided in Figure 4. The values for z_{wake} are positive for locations above the wake axes plane and negative below the wake axes plane.

The mapping is complicated by the orientation of the aircraft relative to the wake. Figures 5-7 show the effect of varying bank angle, pitch attitude and heading on the mapping presented in Figure 4.

5. Provide the value for stabilizer setting required to trim before the accident sequence, and compare to the trim setting at impact.

Figure 8 presents the time history of derived stabilizer position for the USAir 427 accident. The initial stabilizer value is that required to trim the simulation in a 3° descent at idle thrust, 190 KCAS with a flaps 1, gear up configuration, given the estimate of weight and C.G. of 109,000 lbs and 19% MAC, respectively.

The nose-down stabilizer input from time 112-115 is required to trim as the aircraft leveled off at 6000 feet and thrust was increased from idle to about 60% N1. The rate of trim is consistent with the autopilot trim rate of 0.2 deg / sec and occurs during the time when the stabilizer trim wheel is heard on the CVR to be turning at the autopilot trim rate.

The nose-up stabilizer input starting at time 150 is an estimate of the stabilizer trim activity required to change the stabilizer position from the required trim value at time 130 to the stabilizer position recorded at the impact site. The rate used in the estimate is the flaps down stabilizer trim rate of 0.6 deg / sec.

6. Provide the gains for the autopilot.

Figure 9 presents a depiction of the autopilot heading and roll attitude-to-wheel gains.

The error generated between MCP selected heading and actual heading is fed through an MCP selectable bank angle limit and a ±4 deg / sec roll rate limit to the summing junction with roll attitude feedback.

Example:

For a heading error of 10° and a selected bank angle limit of 20°, the heading input to the summing junction will ramp up at 4 deg / sec until it equals 20°. This 20° represents an aileron command of (20.0 * 2.1 * 0.64°). This, however, is further limited by the software to an actual output of 15°. This software output is multiplied by a mechanical gain of 3.5 but is again limited downstream by the mechanical force limiter to approximately 25° wheel for a flaps down configuration and 17° wheel for the flaps up configuration.

As the airplane rolls, the roll attitude feedback into the summing junction begins to reduce the aileron command. For this flaps down scenario, when the roll attitude gets to approximately 15°, the wheel will start to move back toward zero (20-(25 / (3.5 * 0.64° * 2.1))). When the airplane bank angle gets to 20° the wheel will be centered.

When the heading error get less than approximately 5° (20° / 3.8) the wheel will move in the other direction to start to roll the airplane back to wings level. At wings level the inputs and outputs of the summing junction will all be zero.

At this flight condition, approximately 5° of roll attitude into the summing junction above that necessary to balance the heading error, can drive the wheel to 25°. Therefore any scenario (including external wake upsets) which produces a summing junction error will quickly drive the wheel to the autopilot mechanical limit.

In addition to the roll attitude error at the summing junction there is another contribution from roll rate which also drives the wheel at a gain of 0.85° of wheel command per deg/sec of roll rate. This will help drive the wheel to its limits as a function of roll rate at less than those values given for only roll attitude as explained above.

7. **Produce a time history of the free response (no control inputs) of a 737-300 to the derived wake encounter time history.**

   Figures 10-11 present the free response of the 737-300 simulator to the wake-induced aerodynamic coefficients derived for the USAir 427 accident. The simulator was trimmed initially in level flight at the condition and configuration corresponding to that for USAir 427 at the initial upset.

8. **Provide data comparing the crossover speed characteristics of the 737-300 simulation using the last published revision of the aerodynamic data to those using the updated aerodynamic data from the Atlantic City flight test.**

   These data are included in the Reference document.

9. **Calculate the full rudder, full wheel crossover speed characteristics of the 737-300 while pulling an incremental load factor equivalent to the load factor for a steady 30° level flight turn.**

Figure 12 shows the full wheel, full rudder crossover speed as a function of weight for a steady heading sideslip and in a turn with a bank angle offset of 30° of that required for the steady sideslip. The incremental load factor between the two maneuvers was 0.155 g's, which is equivalent to the increment in load factor required to perform a steady, non-sideslipped 30° level flight turn.

10. **Develop a computer animation video of the USAir 427 accident with a overhead perspective of the wake encounter.**

This video viewpoint has been added to the video which accompanies the Reference document.

11. **Provide an additional USAir 427 accident time history comparison of a 4 second rudder ramp starting at time 135.5 with the FDR data.**

These data are included in the Reference document.

Table 1. Flight Test Conditions Used to Develop Empirical Wake Yawing Moment Model

Test No.	Sequence Number	Condition Number	Manuever Description	Yaw Damper	Control	Trailing Distance	IRIG at Time = 0
19-07-1	008719	B1.41.0065.002.1	Intercept at 5 deg from right	ON	PILOT	4*	10:47:12.95
19-07-1	008722	B1.41.0065.003	Intercept at 5 deg from left	ON	AUTOPILOT	4*	10:51:22.90
19-07-2	008751	B1.41.0065.013	Left turn onto right core	ON	PILOT	3*	14:42:49.95
19-07-2	008762	B1.41.0065.018	Left turn onto descending rt core	ON	PILOT	3*	15:20:24.85
19-07-2	008765	B1.41.0065.018.3	Left turn onto descending rt core	ON	PILOT	3*	15:24:07.80
19-08-1	008775	B1.41.0065.002	Intercept at 2 deg	ON	PILOT	3.0	07:50:43.25
19-08-1	008778	B1.41.0065.001.1	Intercept at 2 deg	OFF	FREE	3*	07:53:53.25
19-08-1	008781	B1.41.0065.006	Intercept at 5 deg	ON	PILOT	3*	08:01:13.20
19-08-1	008786	B1.41.0065.005.4	Intercept at 5 deg	OFF	FREE	3*	08:14:03.15
19-08-1	008790	B1.41.0065.009.1	Intercept at 2 deg	OFF	FREE	3*	08:19:33.15
19-08-1	008791	B1.41.0065.009.2	Climbing intercept at 2 deg	ON	FREE	3*	08:21:13.15
19-08-1	008792	B1.41.0065.009.3	Climbing intercept at 2 deg	OFF	FREE	3*	08:22:33.15
19-09-1	008815	B1.41.0065.009.2	Climbing intercept at 2 deg	OFF	FREE	2.1	07:49:29.95
19-09-1	008826	B1.41.0065.001.6	Intercept at 2 deg	OFF	FREE	2.9	08:29:29.80
19-09-1	008829	B1.41.0065.021.3	Straight thru descending wake	ON	FREE	3*	08:37:49.75
19-10-1	008853	B1.41.0065.009	Climbing intercept at 2 deg	ON	FREE	4.0	07:16:08.05
19-10-1	008854	B1.41.0065.009.1	Climbing intercept at 2 deg	OFF	FREE	4.3	07:17:38.05
19-10-1	008857	B1.41.0065.021	Straight thru descending wake	ON	FREE	4*	07:21:03.05
19-10-1	008877	B1.41.0065.001.4	Intercept at 2 deg	ON	FREE	2.1	08:06:47.85
19-10-1	008878	B1.41.0065.001.5	Intercept at 2 deg	OFF	FREE	2.3	08:07:42.85
19-10-1	008880	B1.41.0065.009.7	Climbing intercept at 2 deg	OFF	FREE	2.2	08:09:57.85

*Nominal target trailing distance is provided when TCAS distance is not available

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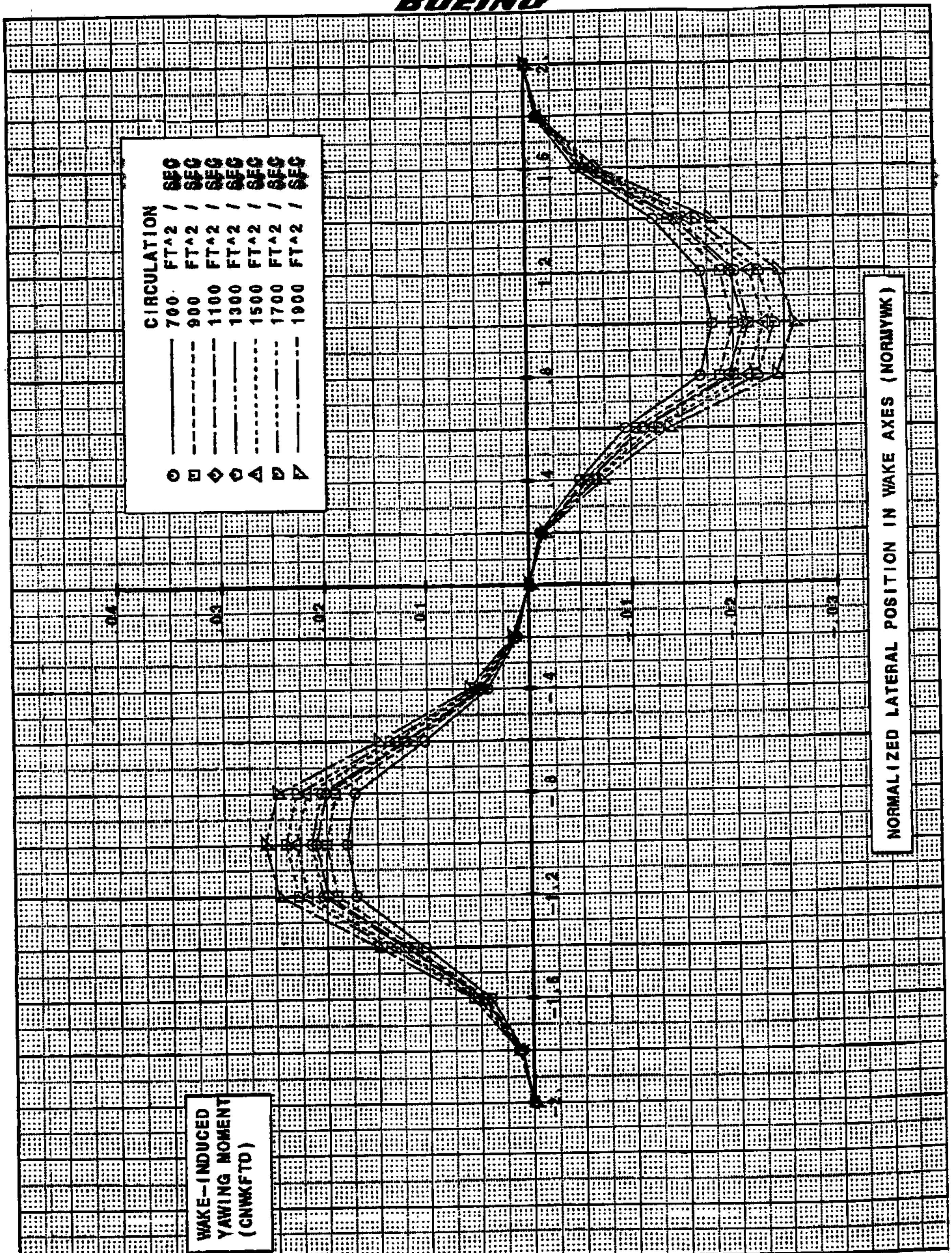
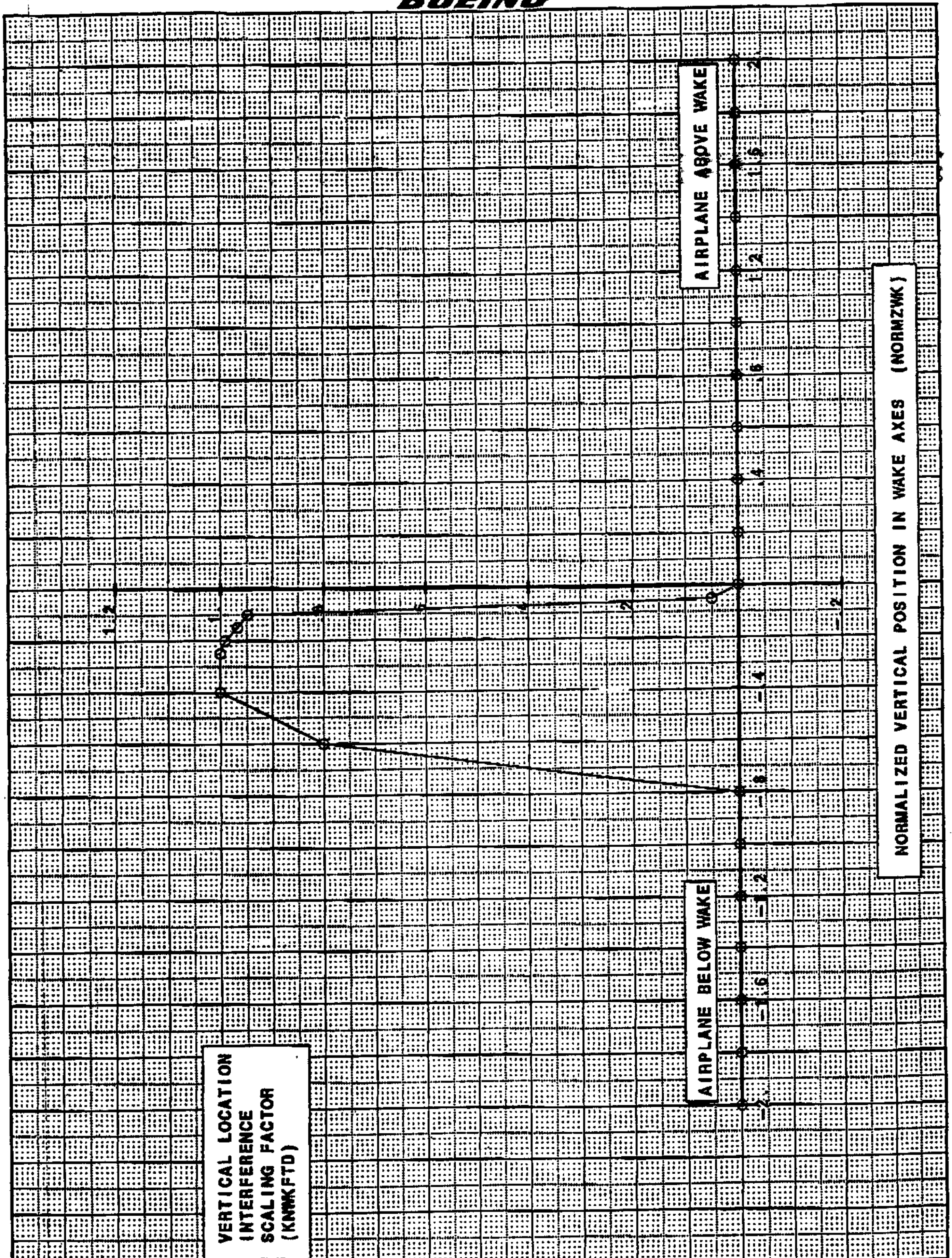


CALC	J. WILBORN	23OCT96	REVISED	DATE	WAKE-INDUCED YAWING MOMENT COEFFICIENT	737-300
CHECK						
APPD						FIGURE
APPD						1

BOEING



CALC	J. WILBORN	23OCT96	REVISED	DATE	EFFECT OF VERTICAL LOCATION OF TAIL IN WAKE AXES ON WAKE-INDUCED YAWING MOMENT	737-300
CHECK						
APPD						FIGURE
APPD						2

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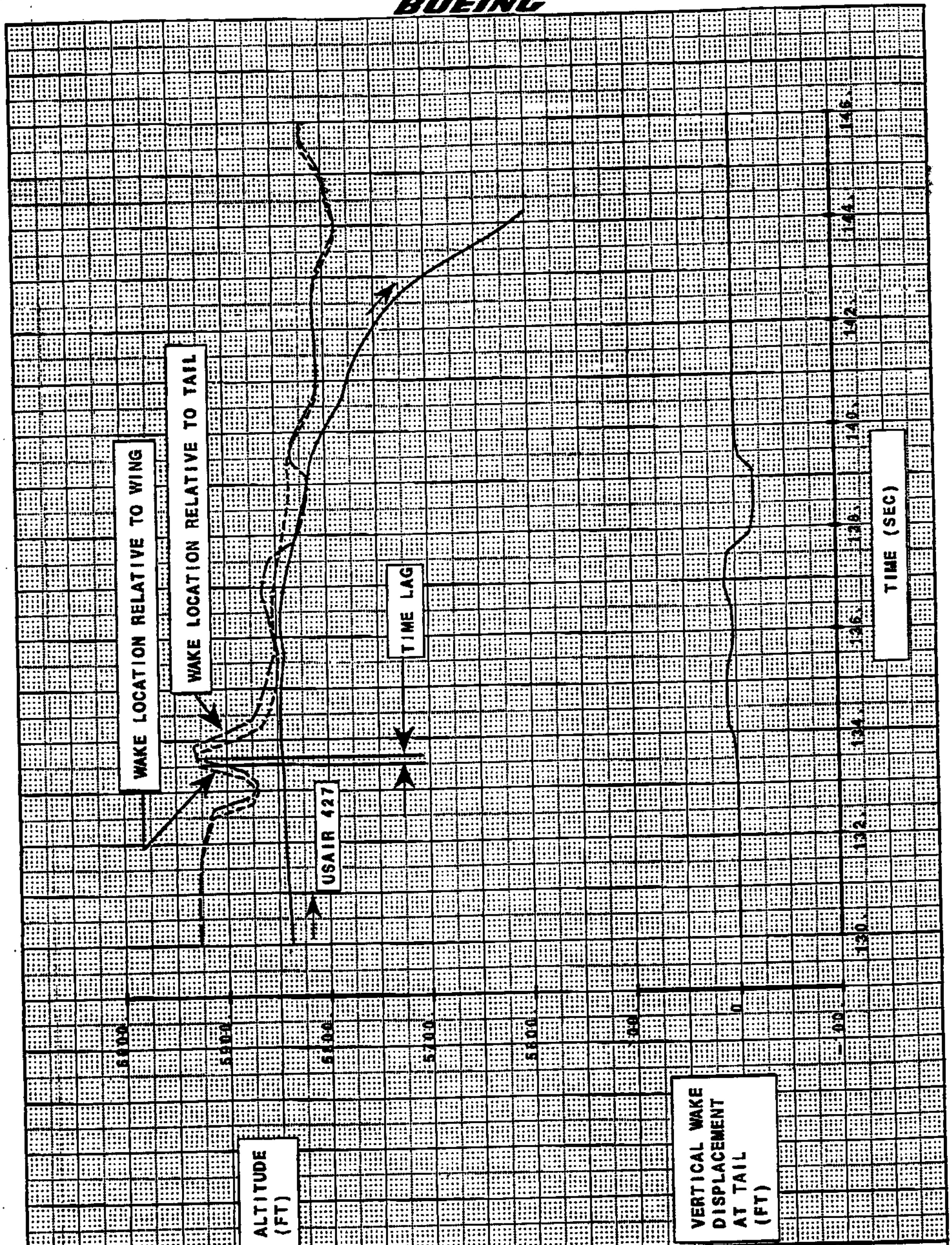

CALC	J. WILBORN	23OCT96	REVISED	DATE	TIME LAG BETWEEN WAKE LOCATION AT WING AND WAKE LOCATION AT TAIL	737-300
CHECK						FIGURE
APPD						3
APPD						

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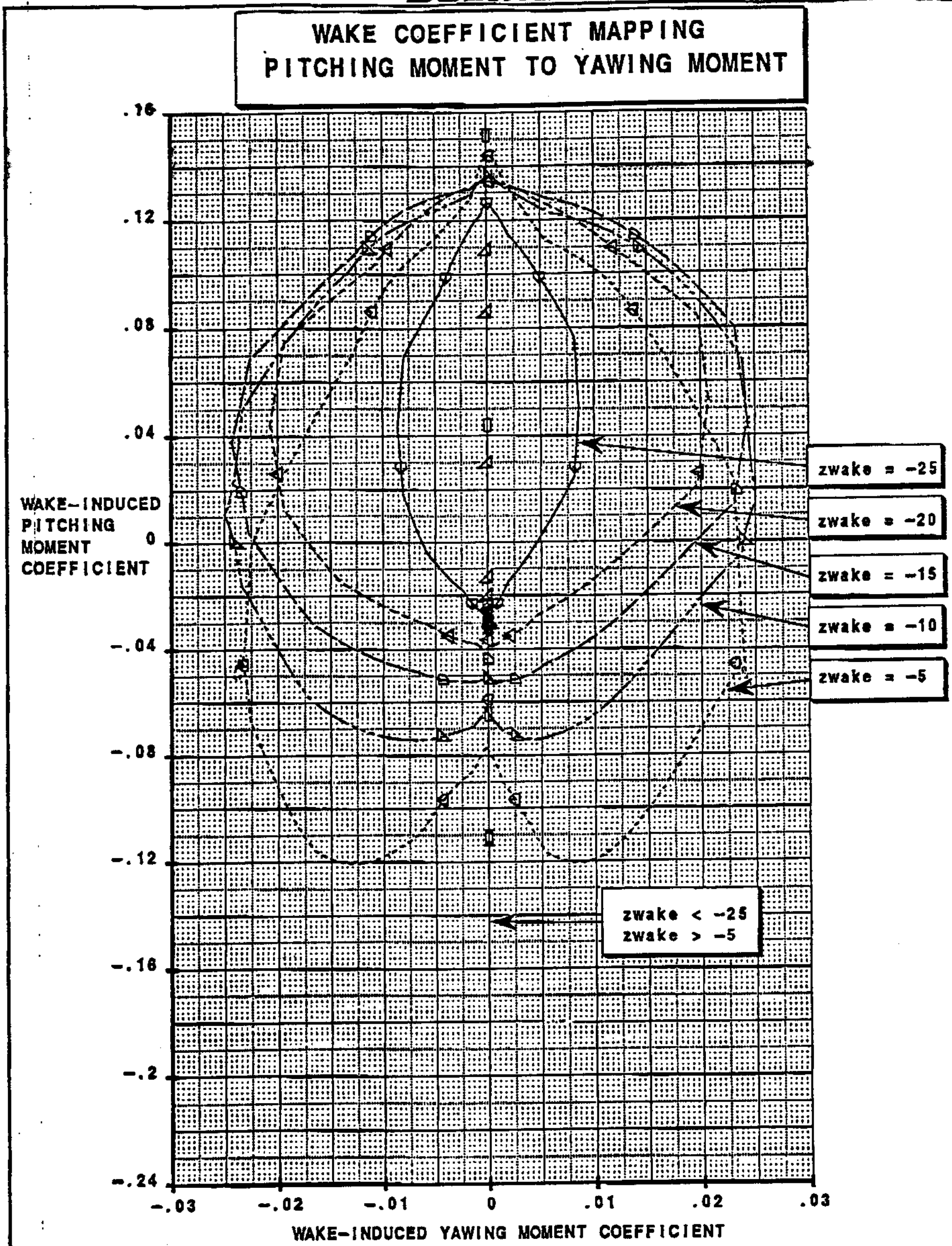

					MAPPING OF WAKE-INDUCED PITCHING MOMENT TO WAKE-INDUCED YAWING MOMENT BANK = 0 PITCH = 0 HEADING = 0	737-300
CALC	J. WILBORN	24OCT96	REVISED	DATE		
CHECK						FIGURE
APPD						4
APPD						

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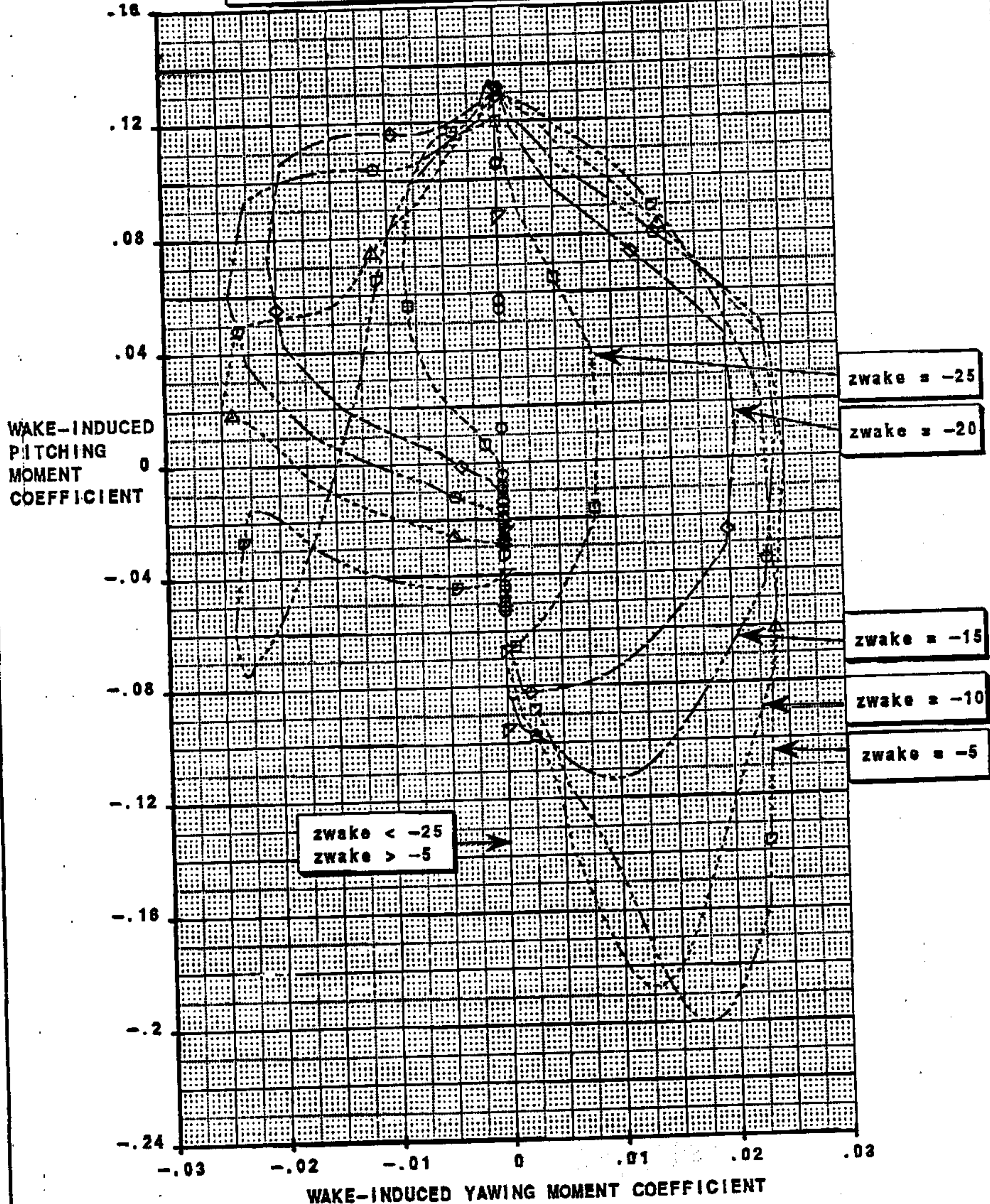
WAKE COEFFICIENT MAPPING
PITCHING MOMENT TO YAWING MOMENT



CALC	J. WILBORN	24OCT96	REVISED	DATE	MAPPING OF WAKE-INDUCED PITCHING MOMENT TO WAKE-INDUCED YAWING MOMENT BANK = -30 PITCH = 0 HEADING = 0
CHECK					
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737-300

FIGURE 5

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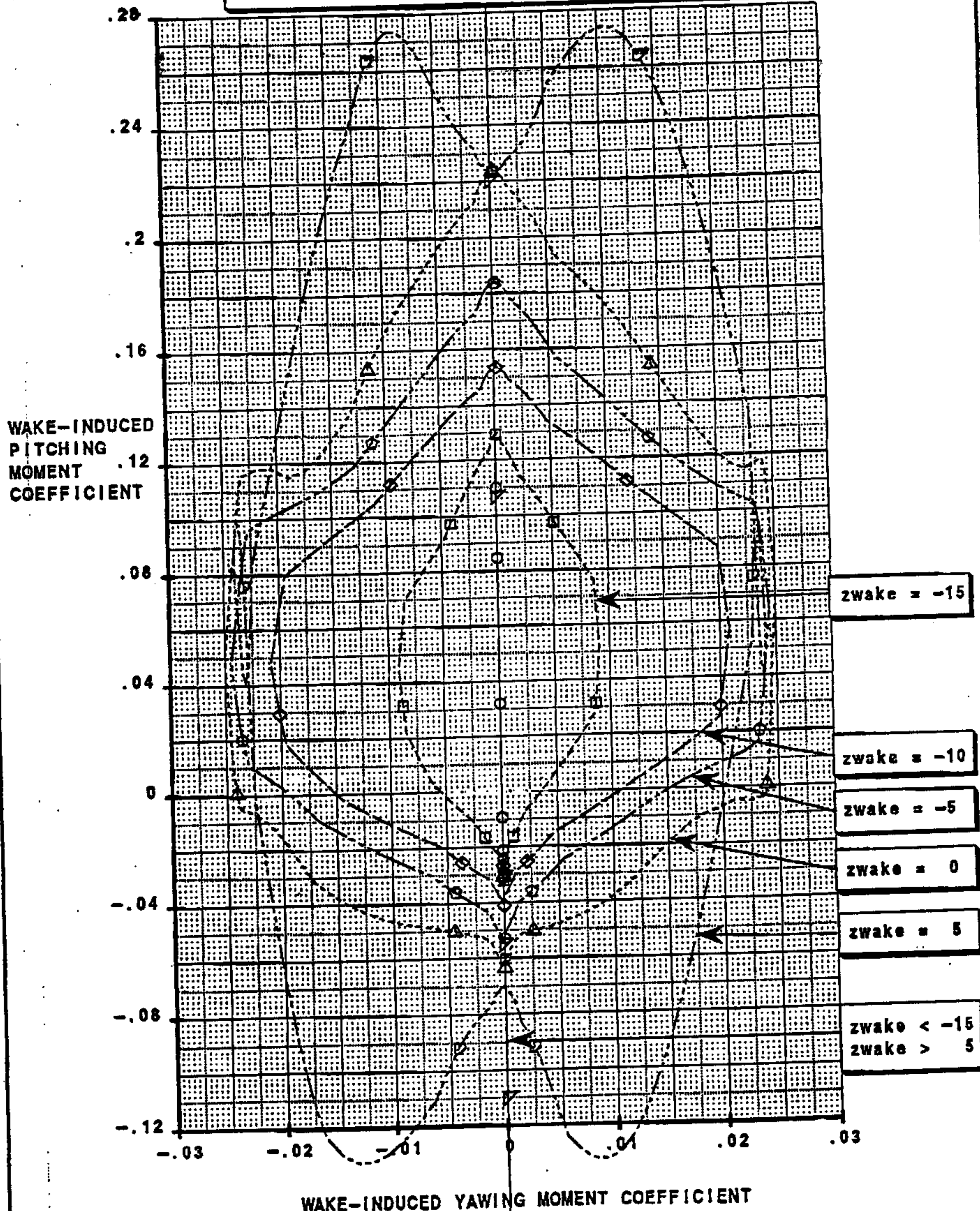
WAKE COEFFICIENT MAPPING
PITCHING MOMENT TO YAWING MOMENT



CALC	J. WILBORN	24OCT96	REVISED	DATE	MAPPING OF WAKE-INDUCED PITCHING MOMENT TO WAKE-INDUCED YAWING MOMENT BANK = 0 PITCH = 10 HEADING = 0	737-300
CHECK						FIGURE
APPD						6
APPD						

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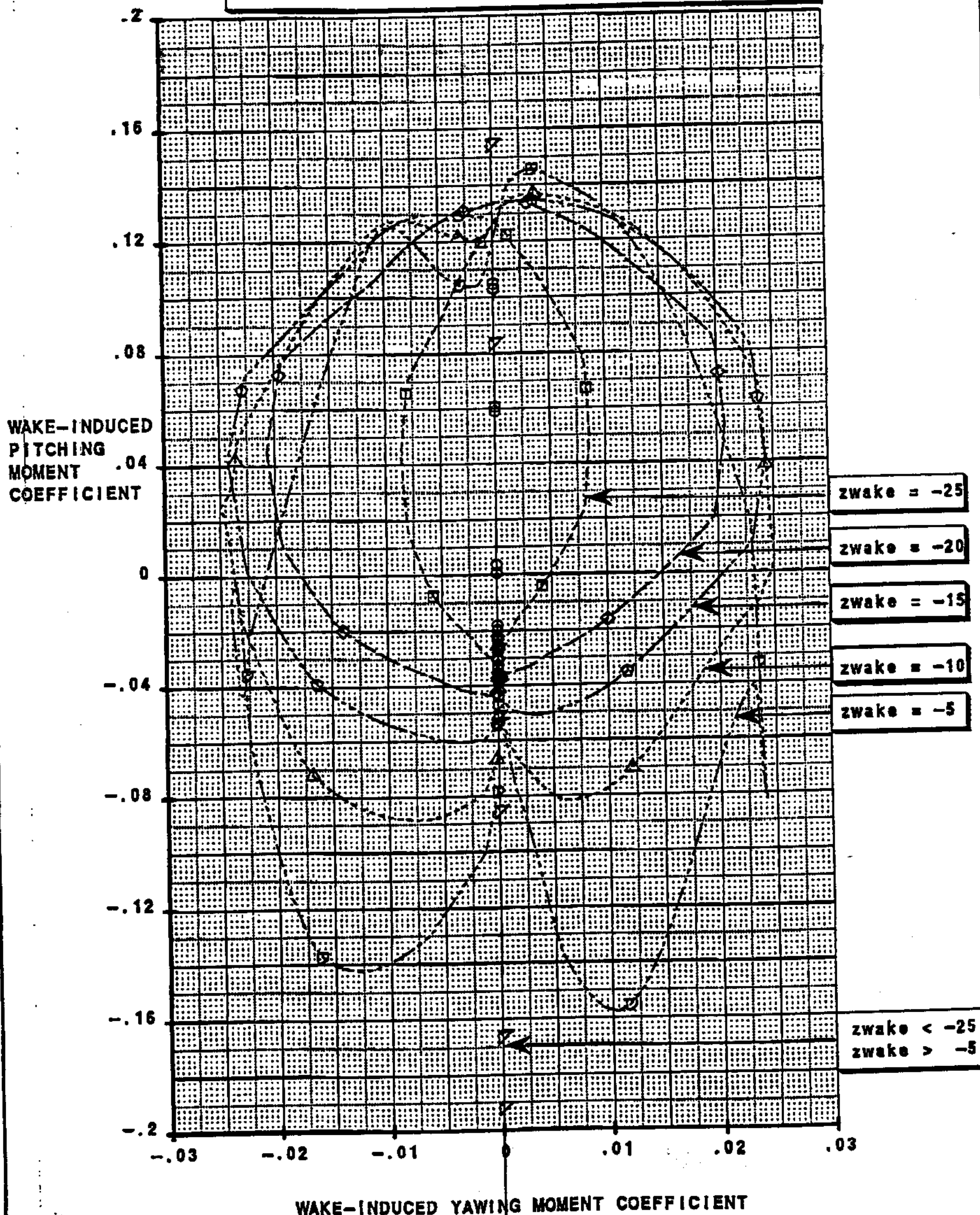
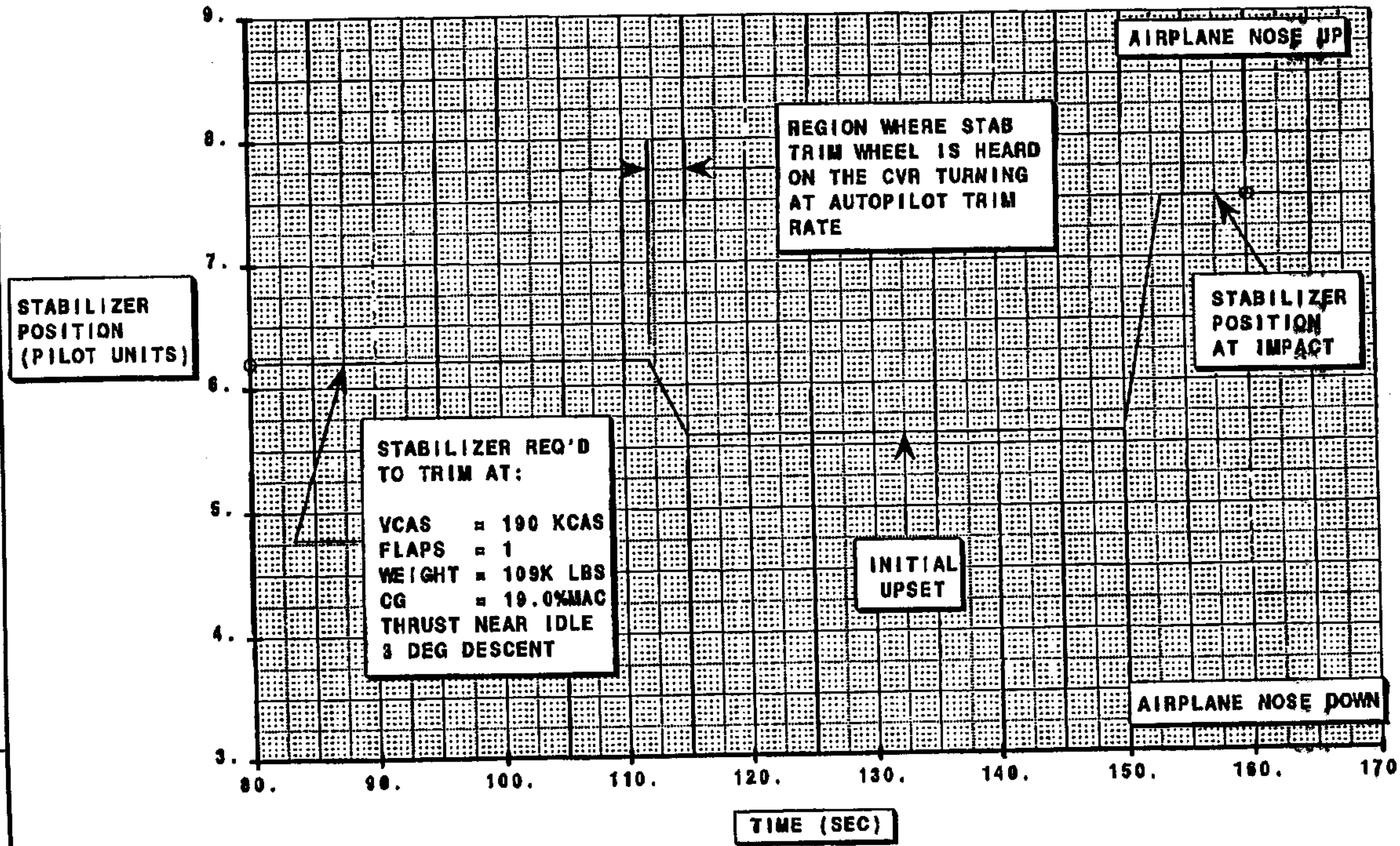
WAKE COEFFICIENT MAPPING
PITCHING MOMENT TO YAWING MOMENT



CALC	J. WILBORN	24OCT96	REVISED	DATE	MAPPING OF WAKE-INDUCED PITCHING MOMENT TO WAKE-INDUCED YAWING MOMENT BANK = 0 PITCH = 0 HEADING = 10	737-300 FIGURE 7
CHECK						
APPD						
APPD						

USAIR 427 DERIVED STABILIZER TIME HISTORY



CALC	J. WILBORN	23OCT96	REVISED	DATE
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DERIVED STABILIZER TIME HISTORY
USAIR 427 ACCIDENT

737-300

FIGURE 8

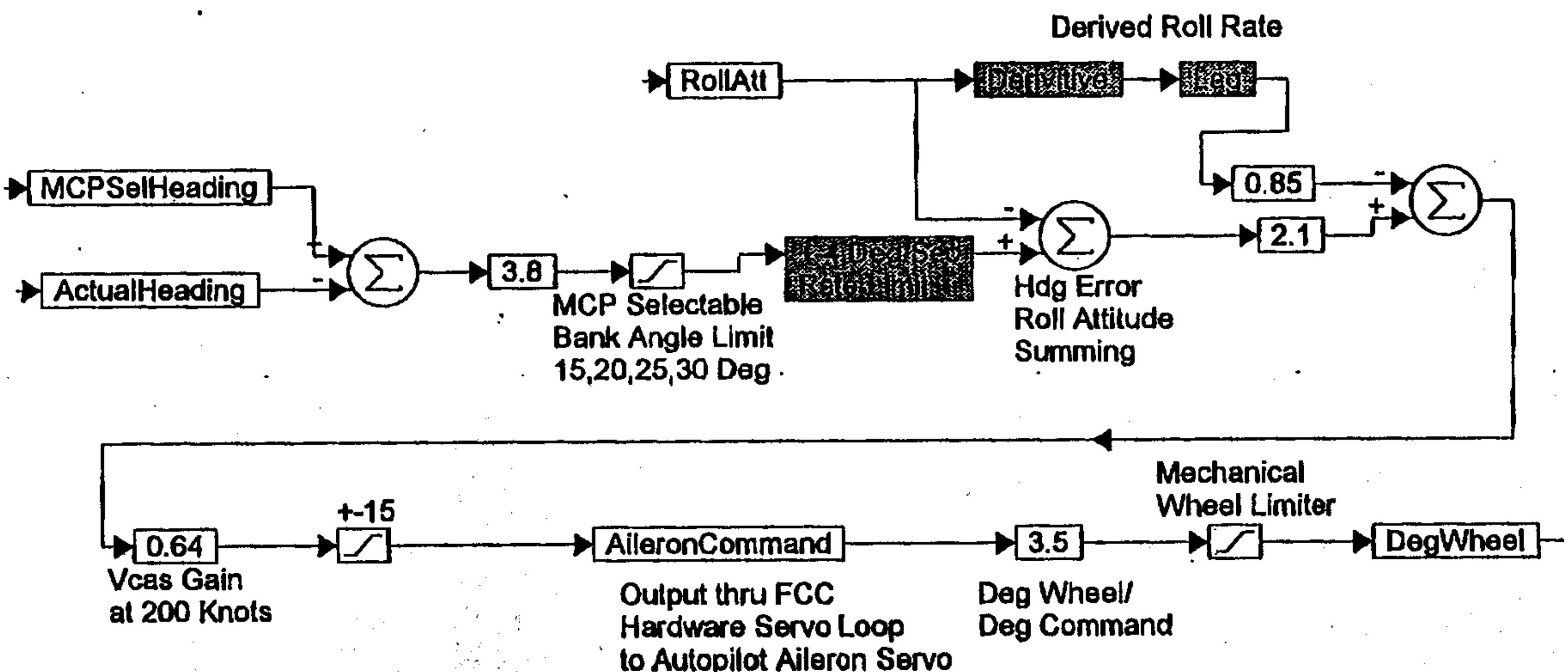

Figure 9. Autopilot System Schematic.

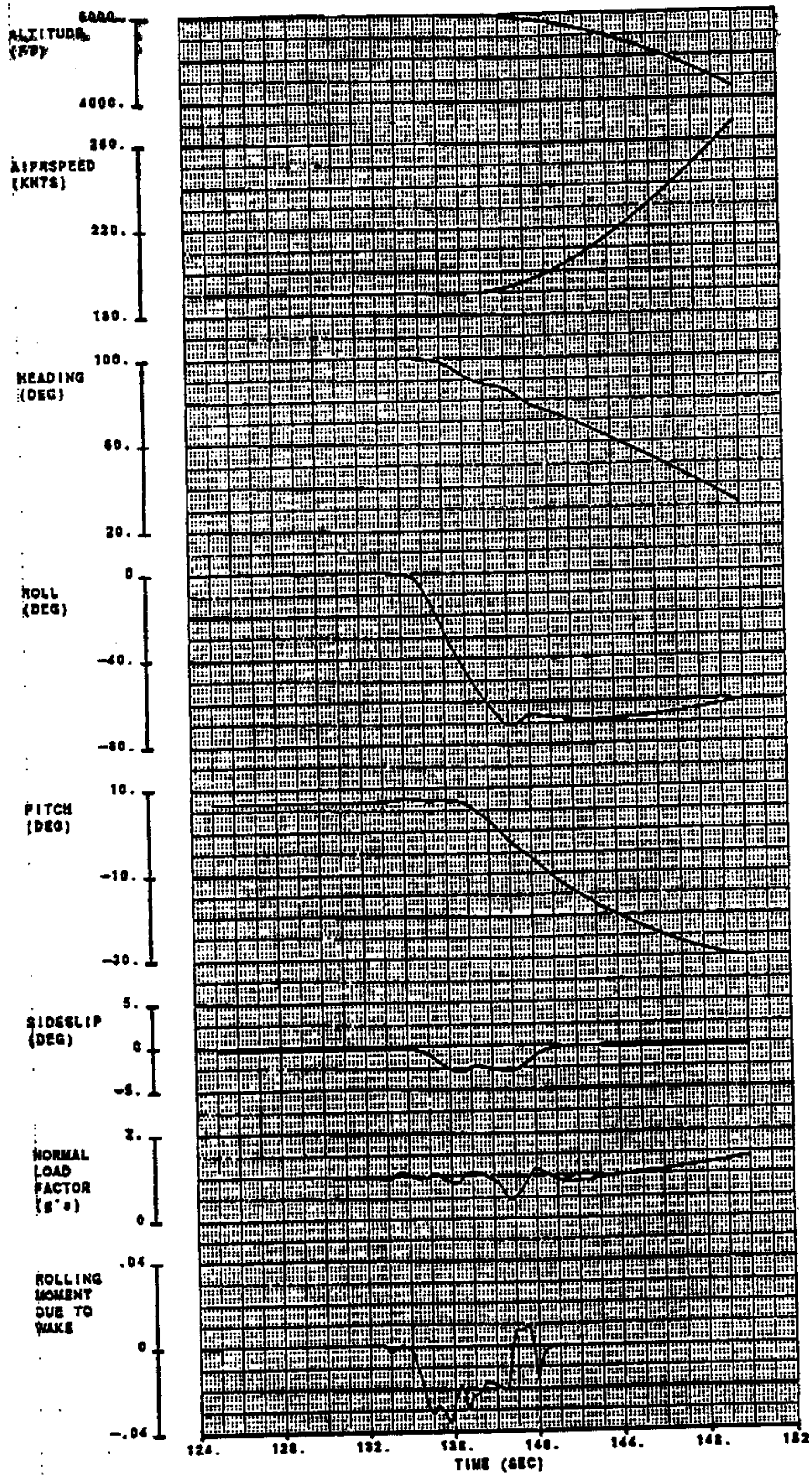

FIGURE 10

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FREE AIRPLANE RESPONSE THROUGH DERIVED USAIR 427 WAKE ENCOUNTER

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FIGURE

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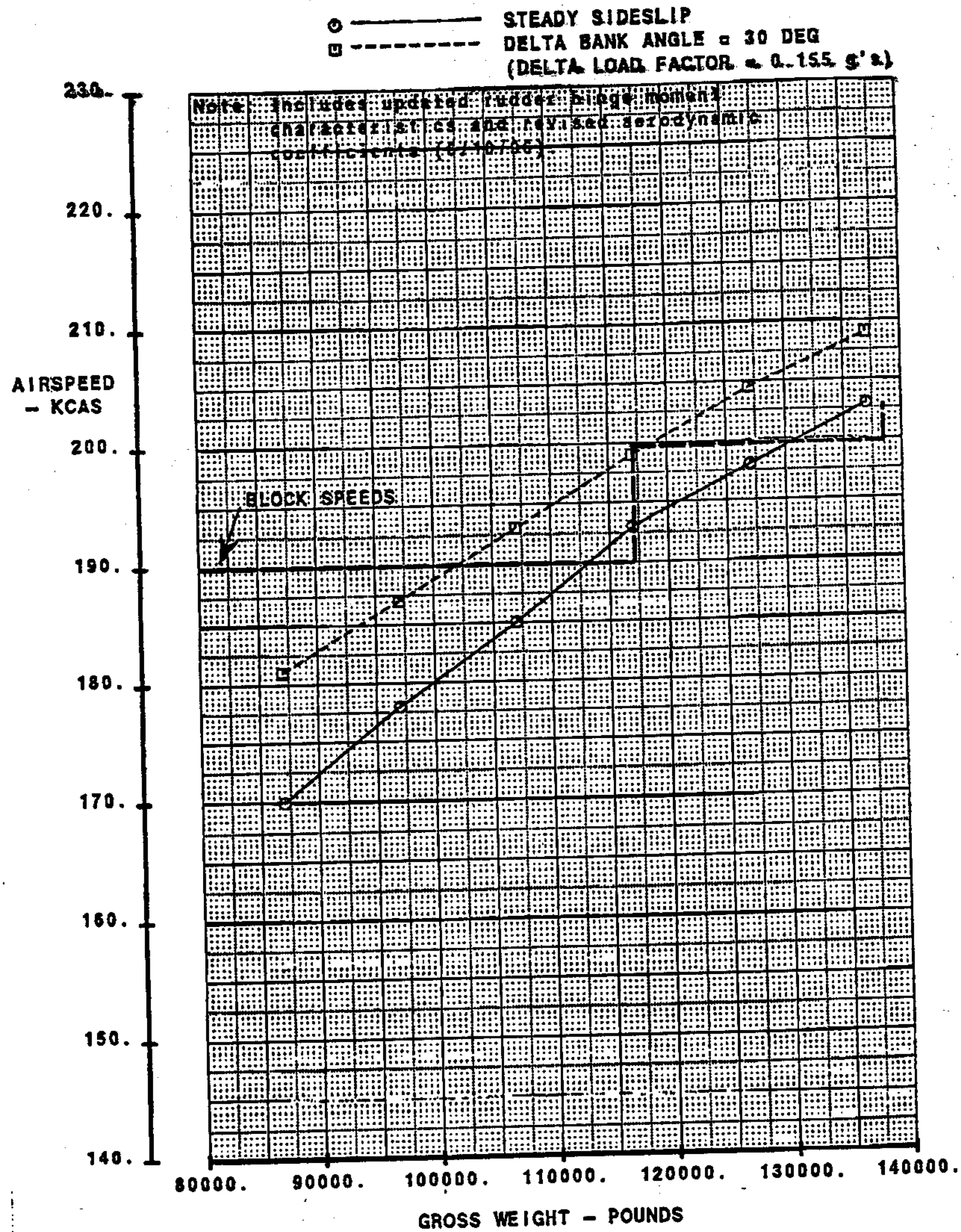
737-300



CALC	B. LEWIS	14OCT96	REVISED	DATE	CONTROL OF FULL RUDDER WITH FULL WHEEL FLAPS 1 CROSSOVER SPEEDS	737-300
CHECK						FIGURE
APPD						12
APPD						