https://ntrs.nasa.gov/search.jsp?R=19920012221 2020-03-17T13:12:27+00:00Z

NASA Contractor Report 189602

P. 37

AN IMPROVED LATERAL CONTROL WHEEL STEERING LAW FOR THE TRANSPORT SYSTEMS RESEARCH VEHICLE (TSRV)

W. A. Ragsdale

UNISYS CORPORATION
Hampton, Virginia

Contract NAS1-19119
March 1992

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

(NASA-CR-189602) AN IMPROVED LATERAL CONTROL WHEEL STEERING LAW FOR THE TRANSPORT SYSTEMS RESEARCH VEHICLE (TSRV) (Unisys Corp.) 37 p CSCL 01C

N92-21454

Unclas
G3/08 0083759

CONTENTS

SUMMARY

A lateral control wheel steering law with improved performance was developed for the Transport Systems Research Vehicle (TSRV) simulation and used in the Microwave Landing System research project. The control law converted rotational hand controller inputs into roll rate commands, and manipulated ailerons, spoilers, and the rudder to achieve the desired roll rates. The system included automatic turn coordination, track angle hold, and autopilot/autoland modes. The resulting control law produced faster roll rates (15 deg/sec), quicker response to command reversals, and safer bank angle limits, while using more concise program code.

INTRODUCTION

Reference 1 describes several Lateral Control Wheel Steering (LCWS) configurations which were developed and tested on the Transport Systems Research Vehicle (TSRV) simulation and aircraft. These configurations were labelled A, B, C, and D for reference. The current (November, 1987) baseline lateral control wheel system is the Configuration C described in Reference 1.

Configuration C is a roll rate command, roll position hold control system. The pilot's wheel input is used to calculate a commanded roll angle, which is displayed on the Electronic Attitude Director/Indicator (EADI). The control system commands aileron and spoiler deflections to bring the actual roll angle, also displayed on the EADI, to the commanded value and maintain it there. The commanded roll angle is essentially the integral of the pilot's wheel inputs. Whenever the commanded roll angle falls within a 2.5 degree deadband from wings level, the system reverts to a track hold submode, maintaining a constant ground track angle. Configuration C includes roll rate damping and turn coordination features, and also generates rudder deflection commands.

During a TSRV simulation of the Microwave Landing System (MLS) at the NASA Langley Research Center in 1986 and 1987, some of the pilots expressed dissatisfaction with the performance of LCWS Configuration C. Some of these problems included:

(1) Roll rates were slower than desired. Typically the maximum roll rate was limited to about 8 deg/sec. In some of the MLS approaches, it was desirable to have a roll rate as high as 15 deg/sec.

(2) Because of the 'integral' roll angle command, it was possible for the aircraft to get completely out of phase with the pilot's commands. This was because the pilot could command a faster rate than the aircraft could achieve. For example, if the pilot held the wheel toward the right for several seconds and then reversed the controls, the aircraft would continue to roll right wing down until the integral of the wheel input changed signs.

(3) There was no limit on the roll angle that could be commanded. Very steep roll angle commands could be generated, especially in view of the phase lag described above.

(4) The roll angle had a tendency to 'bounce back' following a small roll command input. This was especially noticeable during final approaches, when pilots wished to fly with a small roll angle, while the track hold function was attempting to maintain a constant track angle.

Because of these deficiencies, the NASA researcher requested further research to investigate methods of improving lateral control wheel steering performance. Due to the complexity of the LCWS Configuration C program, it was determined that it would be more efficient to design a new control law, rather than to modify the existing one. The result is the LCWS Configuration E described in this report.

ACRONYMS AND PROGRAM SYMBOLS

Acronyms

EADI	Electronic Attitude Director/Indicator
LCWS	Lateral Control Wheel Steering
MFD	Multi-Function Display
MLS	Microwave Landing System
TSRV	Transport Systems Research Vehicle

Program Symbols

ADZ1	wheel input command after deadzone, deg right wing down
AILCMD	aileron deflection command, deg right wing down
AUTO	autopilot engaged, true/false
BETADEG	sideslip angle, deg wind from right
DELA	aileron deflection, deg right wing down
DSPL	left spoiler deflection, deg trailing edge up
DSPR	right spoiler deflection, deg trailing edge up
DWHL	wheel deflection, deg right
FLAPS	flap deflection, deg trailing edge down
GAWH	gain (aileron due to wheel), deg/deg
GDAP	gain (aileron due to roll rate error), deg/deg/sec
GDRB	gain (rudder due to sideslip), deg/deg
GDRDA	gain (rudder due to aileron), deg/deg
GDRQ	gain (rudder QBAR compensator), unitless
GDRR	gain (rudder due to yaw rate), deg/deg/sec
GPHD	gain (aileron due to roll rate), deg/deg/sec
GPLA	roll rate limit in autopilot mode, deg/sec
GPPH	gain (roll rate command due to roll error), deg/sec/deg
GPWH	gain (roll rate command due to wheel), deg/sec/deg
GPW1	roll rate/wheel gain with flaps up at zero knots, deg/sec/deg
GPW2	flap deflection effect on roll rate gain, deg/sec/deg
GPW3	airspeed effect on roll rate gain, deg/sec/knot
GRLEAD	roll reference angle lead time, sec
GXD2R	gravity times degrees to radians constant
IAS	indicated airspeed, knots
LEVTKH	track hold mode engaged, true/false
PEDAL	rudder pedal deflection signal, inches yaw left
PHCTKH	roll command to hold track, deg right wing down
PHDOT	roll rate, deg/sec right wing down
PHICMD	roll angle command, deg right wing down
PHIDEG	roll angle, deg right wing down
PHIDTC	roll rate command, deg/sec right wing down
PHIREF	reference roll angle for roll angle command, deg
QBAR	dynamic pressure, lb/sq ft
RBDEG	body yaw rate, deg/sec yawing right
RCWOD	roll control wheel out of detent, true/false
RK1P	gain (aileron per wheel deflection), deg/deg

RSQLAW	ratio of square law rate command (0=linear 1=square)
RUDCMD	rudder command, deg trailing edge left
SBC	symmetrical spoiler ('speedbrake') command, deg up
SINPHI	sine of roll angle
SQUISH	true if aircraft on the ground (weight-on-wheels)
VGS	ground speed, ft/sec
WHLINP	wheel input after deadzone and shaping, deg
YK1P	gain (rudder due to pedal), deg/inch

GENERAL DESCRIPTION OF LCWS CONFIGURATION E

The basic design requirements for LCWS Configuration E were:

(1) To be able to roll at 15 deg/sec at all airspeeds, and flap and landing gear configurations

(2) To respond immediately to wheel input reversals

(3) To hold roll attitude when the wheel input was released

(4) To maintain ground track angle when the roll angle command was nearly zero

(5) To limit the roll angle command to 45 degrees

(6) To maintain sideslip approximately zero at all times unless the pilot commanded a sideslip via the rudder pedals

(7) To display both the roll angle command and actual roll angle on the EADI

(8) To be compatible with roll autopilot and autoland modes

(9) To exhibit desirable lateral/directional flying qualities, including Dutch Roll damping, roll subsidence, and spiral mode

In the MLS study the TSRV was flown with a two-axis sidearm controller using position angle feedback for control. The controller included hydraulically generated force feedback to the pilot. Although the MLS simulation was actually flown with a sidearm controller, in the following discussion, lateral stick deflections will be referred to as "wheel" deflections, since they are equivalent commands.

Lateral Control Wheel Steering Configuration E (LCWS E) was basically a roll rate command system. The rate command versus wheel deflection could be varied, for research purposes, from a straight linear to a square law quadratic function. There was a small deadband, which could be varied, near zero deflection to avoid analog noise or bias. Maximum wheel deflection (15 deg) generated a roll rate command of 15 deg/sec. Figure 1 depicts the roll rate command versus wheel deflection shaping function.

The roll angle command, or roll reference, was generated by summing the present roll angle plus 0.5 times the roll rate command. This effectively anticipated that, if the wheel was released, the aircraft would stop rolling in 0.5 sec, and then maintain that attitude. In autopilot or autoland modes, the roll angle command was input from the guidance program. The commanded roll angle was shown on the EADI as an open arrowhead, while the actual roll angle was shown as a closed arrowhead. This made it possible for the pilot to anticipate the final roll angle even during high roll rate maneuvers.

The roll rate command was limited to 15 deg/sec when the roll angle was less than 30 degrees. The limit roll rate command was linearly reduced from 15 deg/sec at 30 deg roll to zero at 45 deg roll. This prevented the aircraft from rolling more than 45 degrees. If the wheel was returned to detent with a roll angle over 30 degrees, the roll angle would decay back to 30 degrees.

Track angle hold was engaged only when the wheel was in detent and the roll angle command was less than 0.25 deg (versus 2.5 deg in LCWS C).

The directional control law resulted in a nearly wings-level sideslip (crab) when the pilot pushed and held a rudder pedal deflection.

It was not possible to achieve the desired 15 deg/sec roll rates at all airspeeds with the use of ailerons alone. The control implementation on the simulator included an asymmetrical spoiler deflection command whenever the aileron command exceeded 5 deg. Control authority for both ailerons and spoilers was limited to 50 percent of the TSRV control surface deflection limits.

Despite the informal implementation and evaluation of LCWS E, it met the specified requirements, and was used during the formal data collection runs for the TSRV MLS project. Approximately a dozen pilots flew the simulation. Pilot opinions and comments were generally favorable.

DETAILED CONTROL LAW DESCRIPTION

Figures 2, 3, and 4 are block diagrams of the LCWS E control laws. Appendix A shows the relationship between control gains and the vehicle dynamic response. Appendix B is a listing of the FORTRAN code used in the control law program.

The control system functions and gains used in LCWS E were derived by analyzing the aircraft's closed loop lateral and directional transfer functions, as shown in Appendix A. Gains were tuned to produce the desired response characteristics, and confirmed by pilots flying the real-time simulation program.

The pilot's wheel input, DWHL, in degrees, was first passed through a deadzone of 0.25 deg to avoid analog noise or bias signals. This deadzone could be varied for research purposes. The value after the deadzone, ADZ1, was input to a shaping function (Figure 1). The shaping function could be varied from a linear output proportional to ADZ1, to a quadratic function proportional to ADZ1 squared. Any shaping between these limits could be generated via a term called RSQLAW, which was 0.0 for a linear shaping, and 1.0 for the quadratic shaping. Pilot opinion varied considerably on the value for the shaping, and was not always consistent for the same pilot. The most commonly used value was 0.25. The pilot who had the most experience with sidearm controllers (on the A320 Airbus) preferred quadratic shaping (RSQLAW=1.0).

The shaping function was designed to output a maximum of 15 deg/sec roll rate command for maximum wheel deflection, which was 15 degrees. As shown in Figure 2, the output of the shaping function, WHLINP, was multiplied by a gain function, GPWH, to compensate for variation of the airplane's roll damping tendencies. GPWH was an empirically derived function of the flap deflection, FLAPS, and indicated airspeed, IAS :

$$GPWH = GPW1 + GPW2 * FLAPS + GPW3 * IAS \qquad [1]$$

The actual roll rate feedback, PHDOT, was multiplied by a gain, GPHD, and subtracted from the roll rate command, PHIDTC, to produce the roll rate error signal. The roll rate error was then multiplied by a QBAR compensator, equal to 200/(QBAR+10), to produce the aileron deflection command, AILCMD.

For testing purposes only, a direct aileron command bypass was available, which would deflect the ailerons in direct proportion to the wheel command, WHLINP. The aileron command was the product of a constant gain, GAWH, and the wheel input, WHLINP. GAWH had a nominal value of .667, such that a maximum 15 deg wheel deflection produced an aileron deflection of 10 degrees. This option was selected whenever the roll rate feedback gain (GPHD) was set to zero, instead of the nominal value of 1.0.

While the wheel was out of detent, the reference roll angle, PHIREF, was calculated:

PHIREF = PHIDEG + GRLEAD * PHDOT [2]

In this case, PHIREF was the anticipated roll angle at GRLEAD seconds ahead of the present time, and was displayed as the roll angle command on the EADI. When the wheel was returned to detent, the reference roll angle, PHIREF, was automatically maintained. A constant value of 0.5 sec was used for GRLEAD.

When autopilot or autoland modes were engaged, or when in Track Hold mode with the pilot's roll command nearly zero, PHIREF was set equal to the roll angle command generated by the guidance program. The difference between PHIREF and the actual roll angle, PHIDEG, was multiplied by a gain, GPPH, to produce a roll rate command, PHIDTC. After being limited to a magnitude of 10 deg/sec, this roll rate command was compared with the actual roll rate feedback, as described above, to produce an aileron command. The aileron deflection command was limited to 10 deg, which is half the actual control authority available.

The asymmetrical spoiler deflection (for roll control) command was generated by passing the aileron command through a 5 deg deadzone as shown in Figure 3. No spoilers were commanded until the aileron command exceeded 5 degrees. The asymmetrical spoiler command was limited as a function of flap deflection, to 20 deg with flaps up, and 10 deg with flaps down (40 deg). Finally the symmetric (for lift/drag control) and asymmetric (for roll control) spoiler commands were added and limited before being input to the spoiler actuator model.

As shown in Figure 4, the rudder deflection command was generated by inputs from the aileron deflection, turn rate, roll angle, sideslip angle, and rudder pedals. The rudder pedal component was directly proportional to rudder pedal deflection signal, PEDAL.

Turn coordination was achieved by comparing the turn rate corresponding to a coordinated turn at the present roll angle and velocity,

Coordinated Turn Rate = GXD2R * SINPHI / VGS [3]

with the actual turn rate, RBDEG. (The actual value of a coordinated turn rate is proportional to TAN (PHI) rather than SIN (PHI). SINPHI was used to avoid problems at steep roll angles.)

The turn rate error was multiplied by a constant gain, GDRR, and summed with other terms to oppose sideslip, GDRB * BETADEG, and adverse yaw due to ailerons, GDRDA * DELA * FLAPS, then multiplied by a QBAR compensating gain, GDRQ/(QBAR + 10).

After weight-on-wheels (SQUISH) had occurred, the rudder was driven only by the rudder pedal component, YK1P * PEDAL. Otherwise, the rudder command was a combination of the rudder pedal and turn coordination terms.

SIMULATION RESULTS

Figures 5 to 10 show the responses of the TSRV MLS simulation to step inputs in the wheel deflection, under conditions as shown in Table 1.

TABLE 1

Figure	Airspeed	Flaps	Landing Gear
5	130	40	Down
6	170	15	Down
7	200	Up	Up
8	250	Up	Up

Figure 9 shows the dynamics of the aircraft and controls during a wings level crab maneuver, and Figure 10 shows a time-history of lateral dynamics and controls during an MLS autoland approach, beginning 3000 ft off the planned path.

The variables plotted in these figures are as follows:

DWHL wheel deflection in degrees
ROLL RATE in deg/sec, rolling right positive
ROLL roll angle in degrees, right wing down positive
DELA aileron deflection in deg, positive to generate right roll
DSPL left spoiler deflection in deg, positive to generate left roll
DSPR right spoiler deflection in deg, positive to generate right roll
DELR rudder deflection in deg, positive to generate left yaw rate
BETA sideslip in deg, positive when relative wind from right
PEDAL rudder pedal deflection in inches, positive to generate left yaw

The step input responses were generated during a batch run (not real-time). The sequence of events during these runs are as follows:

t = 0 sec Wheel deflected to maximum positive (right) deflection
t = 10 sec Wheel deflected to maximum negative (left) deflection
t = 13 sec Wheel returned to neutral

Figure 5 was generated at 130 knots, with the flaps fully extended to 40 deg, and the landing gear down. The 15 deg/sec roll rate was achieved in about 1.5 sec. At 2.5 sec the roll angle had reached 30 deg, so the roll rate began to decrease automatically, reaching zero at about 45 deg of roll. The 45 deg roll was held until the wheel was deflected back to full left at 10.0 sec. The roll rate response was immediate. When the wheel was released at 13.0 sec, to command a roll rate of zero, a small overshoot occurred. The ailerons are quite active during these maneuvers, and some spoiler deflections are required to achieve the commanded rates. Rudder motions occur mainly when the roll rate command changes. Sideslip remains within 2 degrees of zero throughout the maneuvers, and is very well damped.

Figure 6 was made at 170 knots, with the flaps set at 15 deg, and the landing gear down. The response is nearly identical to that in Figure 5, but the required aileron and spoiler deflections are larger, and reached the allowable limits of 10 deg aileron and 20 deg spoiler (one-half the total control authority). Rudder deflections were smaller, and sideslip was reduced slightly.

Figure 7 was generated at 200 knots with landing gear and flaps up. Although maximum allowable aileron and spoiler deflections were used, the maximum roll rate achieved was only about 12 deg/sec. The desired 15 deg/sec could have been achieved if the control system were allowed full deflection authority, but for safety purposes, only half the actual total deflection can be commanded by the LCWS. Rudder deflections were further reduced, but sideslip is slightly larger in this case, but stayed within 1.5 deg of zero. (In Reference 1, a similar reduction in control response around 200 knots was noted.)

Figure 8 was generated at 250 knots with landing gear and flaps up. The 15 deg/sec roll rate was achieved without maximum control deflections, although spoilers were required. Rudder deflection and sideslip were essentially the same as before.

It should be noted that these step responses are interesting from a theoretical standpoint, but could not be generated by a pilot, since it is not possible to instantly reverse the control wheel input, as was done in these tests. The response should be slightly smoother with a pilot in the loop.

From these tests, it appears that most of the criteria for the Lateral Control Wheel Steering system (described above) are met by the LCWS E configuration, and the response is approximately the same at different airspeeds and gear and flap configurations.

Figure 9 is a plot of the response to a wings level crab maneuver. In this demonstration, the rudder pedal was pushed at 2.0 sec, and held at a constant deflection until 12.0 sec, then released after a steady state had been achieved. In LCWS E, turns are automatically coordinated without requiring rudder pedal deflections. If a rudder pedal is pushed, the aircraft will sideslip in the normal direction, but the ailerons and spoilers will attempt to maintain the existing roll angle. Essentially, the wheel commands coordinated roll/yaw rates, and the rudder pedals command sideslip.

Figure 10 is a time history of the same variables during an MLS approach in autoland mode. The run was initiated with a 3000 ft crosstrack error. Upon capturing the offset approach path, a right turn toward the localizer was made, followed by a left turn to final. Roll rates were limited to 10 deg/sec in autoland mode (but could have been higher if desired). Roll angle commands were limited to 25 deg. The airspeed varied from 175 to 130 knots during this approach. The landing gear was down, and the flaps were deployed according to the normal schedule. Neither maximum aileron or spoiler deflections were required during this run. Note that the compressed time and vertical scales on these plots make some of the dynamics appear abrupt. They were actually smoother than for the step inputs above.

LCWS configuration E was flown by a number of pilots during the TSRV MLS data collection runs in December, 1986 to June, 1987. The main purpose of that study was evaluation of various EADI and MFD displays during MLS complex path approaches. The flight control system was of secondary importance, but appeared to enhance performance and acceptability of the simulation in general. LCWS E has also been used during EADI display evaluations.

Pilot comments about the lateral control system were generally favorable. But there was a diversity of opinions, especially concerning the square law command shaping function. Some pilots insisted on flying the linear law, because of previous bad experiences with non-linear laws. The most commonly used value for RSQLAW was 0.25 (with zero meaning a linear law, and 1.0 meaning a pure square law, as shown in Figure 1.) In one instance a value of 0.75 was flown for several days, with the pilot thinking he was flying the 0.25 law, due to a misunderstanding of the definition of RSQLAW. He did not notice the difference until the error was discovered. The only pilot in the study who had flown an actual transport aircraft with a sidearm controller (the A320) preferred the pure square law (1.0).

PROBLEMS

Three problems were encountered in this design, as described below.

Aileron Servo Numerical Instability

This simulation was run with an time step of .03125 sec, corresponding to 32 iterations per second. Nevertheless, the aileron servo simulation exhibited numerical instability, due to its short time constant. This problem was solved by passing through the aileron servo simulation algorithm four times for each pass through the main program, resulting in an effective iteration rate of 128 per second. This solved the problem.

It is possible the problem could have been solved more simply by root matching methods similar to those described in Reference 2, but the available time and resources did not permit investigating such alternatives.

Spoiler / Aileron Interconnect

The actual spoiler system on the TSRV aircraft is a complex mechanical system, interconnecting the spoilers, flaps, and ailerons. It exhibits some undesirable characteristics, especially a lot of hysteresis. Since LCWS E requires spoiler deflections to achieve the desired roll rates, this could lead to oscillations.

So for this simulation, the spoilers were modelled as servo-driven (irreversible) controls, following deflection commands in the same manner as the ailerons and rudder, without mechanical interconnects. It is well within the current state-of-the-art to do this on the actual aircraft.

Roll Rate Oscillation Following Control Wheel Reversals

During the TSRV MLS data generation runs, some pilots noticed that for small, quick, reversals of the wheel, the velocity trend vector on the MFD would first move opposite the wheel motion, as adverse yaw does in a conventional aircraft. On Figures 5 and 8 it appears that when the wheel input was returned to neutral at 13.0 sec, the roll rate first moved in the wrong direction (increased) for about 0.2 sec. This may be due to a slightly uncoordinated initial roll/yaw motion. (Note on Figure 5 the rudder also moved in the wrong direction first.) This effect was not noticeable for normal maneuvers, and would not have been noted here, except for the sensitivity of the trend vector to lateral accelerations.

RECOMMENDATIONS

It would be worthwhile to evaluate pilot ratings for this system without their prior knowledge of the control laws, to determine the effects of various control shaping algorithms. Although many pilots can, and do, adapt to almost any control system, there should be some tradeoff between performance and the control law being used. Digital fly-by-wire control systems should not necessarily be limited to those algorithms previously implemented in analog autopilots.

The effects of the spoiler and aileron interaction need to be studied in more detail. The aileron servo model might be improved by using different numerical methods.

The existing LCWS E program code was patched into the LCWS C program (although the LCWS E program code is an order of magnitude smaller). A separate standalone LCWS E program module, independent of LCWS C, should be developed, documented, and maintained as a separate entity that can be used when requested. Some of the coding could be improved or optimized more easily in a separate program module.

Although some runs with crosswinds and turbulence were made during TSRV MLS data collection, no formal evaluation of the effects of turbulence on LCWS E have been made. It certainly did not prevent any successful landings, but ride qualities in adverse weather conditions need to be evaluated.

Flying LCWS E on the motion base simulator would be beneficial in determining qualitative ride qualities in a more realistic environment, especially during turbulence.

CONCLUSIONS

The Lateral Control Wheel Steering Configuration E appears to satisfy most of the requirements for roll and yaw control of the TSRV. It is a straightforward control algorithm, much smaller than previous programs, and yet offers superior performance.

APPENDIX A

CONTROL GAINS AND VEHICLE DYNAMIC RESPONSE

Boeing 737 Lateral/Directional Aerodynamic Coefficient Summary

	VE=200 A=5 DF=0	VE=170 A=2 DF=15	VE=130 A=0 DF=40	
CLB	-.0036	-.0038	-.0044	per deg
CLDA	.00125	.00120	.00140	per deg
CLDR	.0011	.0011	.0011	per deg
CLP	-.48	-.71	-.66	per rad/sec
CLR	.14	.20	.30	per rad/sec
CLDSP	.00045	.000925	.00168	per deg
CNB	.0035	.0035	.0043	per deg
CNDA	-.000015	.000055	.000135	per deg
CNDR	-.0032	-.0032	-.0032	per deg
CNP	0.	0.	-.03	per rad/sec
CNR	-.28	-.24	-.23	per rad/sec
CNDSP	.00010	.00030	.000375	per deg

Notes:

S = wing area = 980 b = wing span = 93
Ixx = roll inertia = 440000 Izz = yaw inertia = 1310000

Positive aileron produces right wing down roll.
Aileron deflection is deflection of single aileron.
Aileron limits are +/-20 deg.

Positive rudder produces nose left yaw.
Rudder limits are +/-25 deg.

Right spoiler produces right wing down roll.
Spoiler deflection limit is 0 to 40 deg.

Maximum flap deflection is 40 deg.

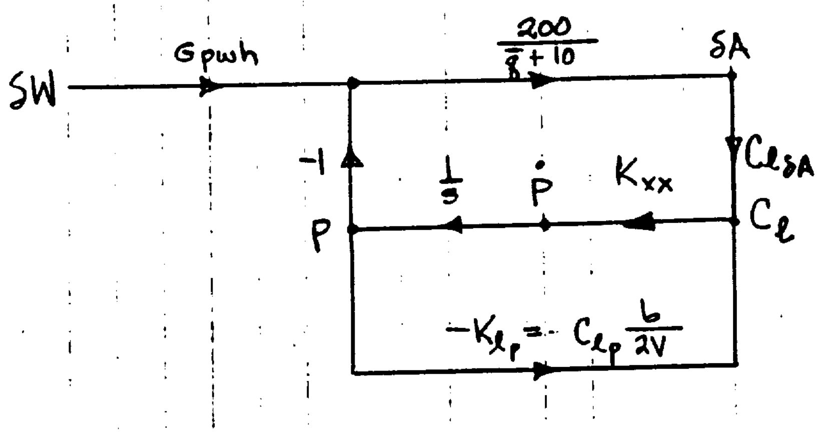
CNDA ranges from .00015 at A=-5 DF=40 to -.00015 at A=20 DF=0.
CLDSP ranges from .00045 with DF=0 to .00168 with DF=40.
CNDSP ranges from .00010 with DF=0 to .000375 with DF=40.

Most other coefficients do not change significantly.

CL = roll moment coefficient		CN = yaw moment coefficient
A = angle of attack	B = sideslip angle	VE = equivalent airspeed
DA = aileron	DR = rudder	DSP = spoiler
DF = flap	P = body roll rate	R = body yaw rate

LCWS E Rolling Transfer Function

RCWOD out of detent



$$K_{xx} = \frac{\bar{q} S b (57.3)}{I_{xx}}$$

$= 676$ @ 130 kts

$K_{l_p} = .00243$ @ 130 kts

$$\frac{p}{\delta W} = \frac{\left(G_{pwh} \frac{200}{\bar{q}+10} C_{l\delta A} K_{xx} \frac{1}{s}\right)}{1 + K_{l_p} K_{xx} \frac{1}{s} + \frac{200}{\bar{q}+10} C_{l\delta A} K_{xx} \frac{1}{s}}$$

$$= \frac{1.4(2.97)(.0014)(676)}{s + 1.643 + 2.81}$$

$$= \frac{3.94}{s + 4.45}$$

$Gain_{ss} = .885 \quad \tau = .225$

Approximately same as real-time results

Note ROLL RATE on Fig. 5 (actual τ is longer, averages about 0.5 sec)

δW = wheel deflection

δA = aileron deflection

p = roll rate

$\dot{p}$ = roll acceleration

C_l = roll moment coeff

$C_{l\delta A} = \Delta C_l / \Delta \delta A$

$C_{l_p} = \Delta C_l / \Delta p$

$\bar{q}$ = dynamic pressure

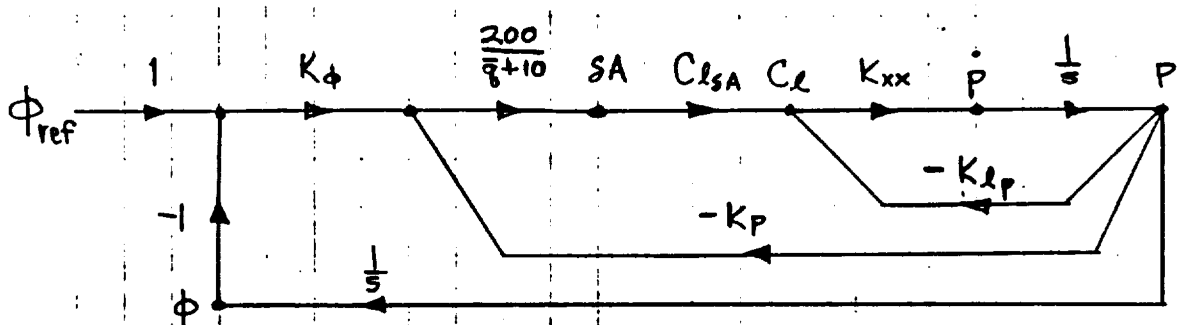
b = wingspan

V = true airspeed

$\frac{1}{s} \Rightarrow$ integral

LCWS E Roll Hold Transfer Function

RCWOD in detent



$$K_{xx} = \frac{57.3\ \bar{q}\ S\ b}{I_{xx}} = 676 \text{ @ } 130 \text{ kts}$$

$K_\phi = 4.$
$K_p = 1.$

$$-K_{l_p} = C_{l_p}\frac{b}{2V} = .00243 \text{ @ } 130 \text{ kts}$$

$C_{l_{SA}} = .0014$

$$\frac{\phi}{\phi_{ref}} = \frac{\left(K_\phi \frac{200}{\bar{q}+10} C_{l_{SA}} K_{xx}\right)}{s^2 + \left(K_{l_p}K_{xx} + \frac{200}{\bar{q}+10} C_{l_{SA}} K_{xx} K_p\right)s + K_\phi \frac{200}{\bar{q}+10} C_{l_{SA}} K_{xx}}$$

$$= \frac{(4(2.97)(.0014)\,676)}{s^2 + [.00243(676) + (2.97)(.0014)(676)(1.0)]s + (4)(2.97)(.0014)(676)}$$

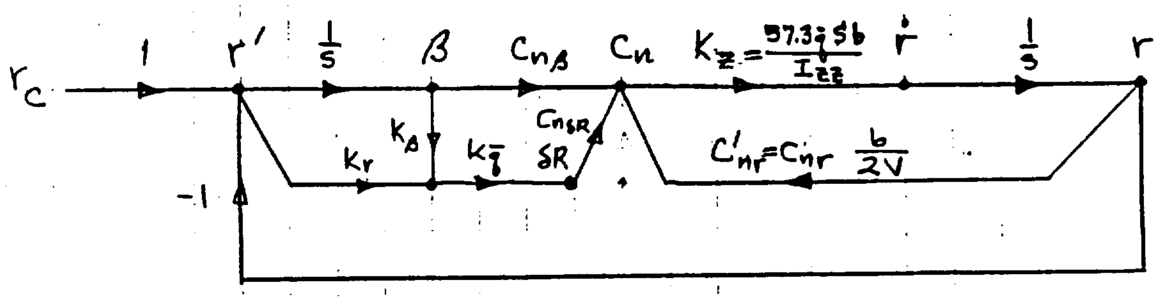
$$= \frac{11.17}{s^2 + 4.45s + 11.17}$$

@ 130 kts $\Rightarrow \bar{q} = 57.3$

$\omega_{n_1} = 3.342$ $T_n = 1.88$ $\zeta = 1.33$

Matches realtime results
Note ROLL on Fig. 5.

LCWS E Turn Coordination



$r_c = \frac{1843 \sin\phi}{V}$ $\quad C_{n_\beta} = .0043 \quad C_{n_{\delta R}} = -.0032 \quad C_{n_r} = -.0040$

$K_Z = 3.98\,\bar{q} \quad K_{\bar{q}} = \frac{67}{\bar{q}+10}$ $\quad$ @ 130 kts $\bar{q} = 57.3$, $V = 220$ fps $\quad K_Z = 228 \quad K_{\bar{q}} = 1.0 \quad C'_{n_r} = .000845$

$$\frac{r}{r_c} = \frac{\frac{1}{s} C_{n_\beta} K_Z \frac{1}{s} + \frac{1}{s} K_\beta K_{\bar{q}} C_{n_{\delta R}} K_Z \frac{1}{s} + K_r K_{\bar{q}} C_{n_{\delta R}} K_Z \frac{1}{s}}{1 + \frac{1}{s} C_{n_\beta} K_Z \frac{1}{s} + \frac{1}{s} K_\beta K_{\bar{q}} C_{n_{\delta R}} K_Z \frac{1}{s} + K_r K_{\bar{q}} C_{n_{\delta R}} K_Z \frac{1}{s} - K_Z C'_{n_r} \frac{1}{s}}$$

$$= \frac{K_Z \left[(K_r K_{\bar{q}} C_{n_{\delta R}}) s + (C_{n_\beta} + K_\beta K_{\bar{q}} C_{n_{\delta R}}) \right]}{s^2 + (K_Z K_r K_{\bar{q}} C_{n_{\delta R}} - K_Z C'_{n_r}) s + (K_Z C_{n_\beta} + K_Z K_\beta K_{\bar{q}} C_{n_{\delta R}})}$$

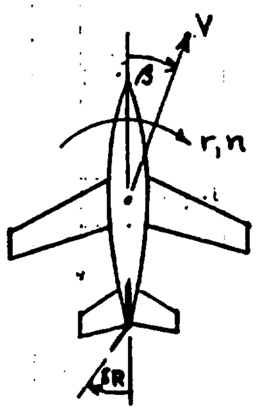
using $K_\beta = -4$ $\quad K_r = -8$ (in the program $k_r = -$GDRR)

$$\frac{r}{r_c} = \frac{228 \left[(.0256\, s + (.0043 + .0128) \right]}{s^2 + (5.84 + .19) s + (.98 + 2.92)}$$

$$= \frac{5.84 s + 3.90}{s^2 + 6.03 s + 3.90}$$

$\omega_n = 1.975 \qquad \zeta = 1.53 \qquad t_{.63} = 1.55$

Positive Directions:



Matches real-time results

Note: BETA on Fig's 5 and 8

APPENDIX B
LISTING OF LCWS E FLIGHT CONTROL PROGRAM

```
***************** LCWSE ENTRY POINT *************************************

*  INPUTS         : DESCRIPTION                        : UNITS : CONVENTION
* ---------------------------------------------------------------------------
*  AUTO           : AUTO FLIGHT CONTROL ENGAGED        : LOGIC :
*  BETADEG        : SIDESLIP ANGLE                     : DEG   : + RW FROM RT
*  DELA           : AILERON DEFLECTION                 : DEG   : + RT WING DN
*  DWHL           : WHEEL INPUT                        : DEG   : + RT WING DN
*  FLAPS          : FLAP DEFELCTION                    : DEG   : + TR EDGE DN
*  H              : ITERATION TIME STEP                : SEC   :
*  IAS            : INDICATED AIRSPEED                 : KNOTS :
*  LOGIC(57)      : SQUARE LAW ACTIVE                  : LOGIC :
*  LOGIC(58)      : LCWS E ACTIVE                      : LOGIC :
*  LOGIC(59)      : SERVO DRIVEN SPOILERS ACTIVE       : LOGIC :
*  PEDAL          : RUDDER PEDAL INPUT                 : INCH  : + YAW LEFT
*  PHDOT          : ROLL RATE                          : DPS   : + RT WING DN
*  PHIDEG         : ROLL ANGLE                         : DEG   : + RT WING DN
*  QBAR           : DYNAMIC PRESSURE                   : PSF   :
*  RBDEG          : BODY YAW RATE                      : DPS   : + YAW RIGHT
*  SBC            : SYMMETRICAL SPOILER DEFLECTION: DEG   : + UP
*  SINPHI         : SINE OF ROLL ANGLE                 :       :
*  SQUISH         : WEIGHT ON WHEELS                   : LOGIC :
*  T              : TIME SINCE SIMULATION START        : SEC   :
*  TABLE(136)     : AUTOPILOT ROLL COMMAND             : DEG   : + RT WING DN
*  TABLE(140)     : MAX ROLL ANGLE FOR TRACK HOLD : DEG   : ABS VALUE
*  TABLE(144)     : SQUARE LAW RATIO 0=LINEAR 1=SQ:       :
*  TCVI2(23)      : ROLL TRIM BUTTON RIGHT             : LOGIC :
*  TCVI2(24)      : ROLL TRIM BUTTON LEFT              : LOGIC :
*  TK             : GROUND TRACK ANGLE FROM NORTH : DEG   : +/-180
*  VCWSE          : VEL CTRL WHL STEERING ENGAGED : LOGIC :
*  VGS            : GROUND SPEED                       : FPS   :
* ---------------------------------------------------------------------------
*  OUTPUTS        : DESCRIPTION                        : UNITS : CONVENTION
* ---------------------------------------------------------------------------
*  AILCMD         : AILERON COMMAND                    : DEG   : + RT WING DN
*  DSPL           : LEFT SPOILER COMMAND               : DEG   : + UP
*  DSPR           : RIGHT SPOILER COMMAND              : DEG   : + UP
*  RCWOD          : WHEEL OUT OF DETENT                : LOGIC :
*  RUDCMD         : RUDDER COMMAND                     : DEG   : + YAW LEFT
*  WHLINP         : WHEEL INPUT AFTER SHAPING          : DEG   : + RT WING DN
* ---------------------------------------------------------------------------
       DATA RSSLM,   WHLM                       /  15.,  15.                   /
       DATA PHIREF,  PHCTKH,  PHRRFL,  TKAREF  /  0.,   0.,     30.,   0.     /
       DATA GRLEAD,  GDAP,    GPPH,    GPLA    /  0.5,  200.,   4.0,   10.0  /
       DATA GPHD,    GAWH,    GPHTK,   GTKF1   /  1.0,  0.667,  2.0,   0.     /
       DATA GPW1,    GPW2,    GPW3             /  1.4,  -.015,  .0045         /
       DATA GDRB,    GDRR,    GDRDA            / -4.0,  8.0,    -.01          /
       DATA GDRQ,    GXD2R                     /  67.,  1843.                  /
       DATA TABLE(140),       RK1P             /  .25,  15.0                   /
```

```
*
******  LCWSE CONFIGURATION E SELECTED **********************************
*
        IF (LOGIC (58) ) THEN
*
***    INITIALIZE VALUES ON FIRST PASS
        IF (T .LE. H) THEN
          PHIREF = 0.
          TKAREF = TK
        ENDIF
*
****** CONTROL WHEEL INPUT DEADZONE
*
        ADZ1     = DZONE (DWHL, -DZWHL, DZWHL)
*
*** LINEAR CONTROL WHEEL INPUT
        WHLINP  = ADZ1 * RK1P
*
*** WHEEL OUT OF DETENT
        RCWOD = ADZ1 .NE. 0.
*
****** SQUARE LAW CONTROL SHAPING
*
*       RSQLAW IS (0...1)  0 = LINEAR   1 = SQUARE LAW
*       RSSLM = MAX WHEEL SIGNAL FROM HARDWARE
*       WHLM  = MAX ROLL RATE COMMAND
*       ADZMAX= MAXIMUM INPUT AFTER DEADBAND
*       DZWHL = WHEEL DEADBAND
*
        RSQLAW = TABLE(144)
*
        IF (LOGIC(57)) THEN
          ADZMAX = RSSLM - DZWHL
          BX = (1.0 - RSQLAW) * WHLM / ADZMAX
          AX2 = (WHLM - ADZMAX * BX) / (ADZMAX * ADZMAX)
*** SHAPED CONTROL WHEEL INPUT
          WHLINP = AX2 * ADZ1 * ABS(ADZ1) + BX * ADZ1
        ENDIF
```

```
*
****** TRACK HOLD ROLL COMMAND
*
***   IF WINGS NEARLY LEVEL SWITCH TO TRACK HOLD MODE
           LEVTKH = VCWSE .AND. .NOT.AUTO .AND. .NOT.RCWOD
     &               .AND. ABS(PHIDEG) .LT. TABLE(140)
*
***   TRACK HOLD MODE
         IF (LEVTKH) THEN
*
***   TRACK REFERENCE SLEW VIA THE ROLL TRIM SWITCH
           IF (TCVI2(23)) TKAREF = TKAREF + H * TKRATE
           IF (TCVI2(24)) TKAREF = TKAREF - H * TKRATE
*
***   TRACK ANGLE ERROR    RESOLVE BETWEEN +/-180 DEG
           TKAERR = TKAREF - TK
             IF (TKAERR.GT. 180.) TKAERR = TKAERR - 360.
             IF (TKAERR.LT.-180.) TKAERR = TKAERR + 360.
*
*** ROLL ANGLE TO HOLD TRACK ANGLE
           PHCTKH = GTKF1 * PHCTKH + (1.0 - GTKF1) * GPHTK * TKAERR
           PHCTKH = XLIM (PHCTKH, -TABLE(140), TABLE(140) )
           PHIREF = PHCTKH
*
*** IF NOT IN TRACK HOLD MODE ZERO TRACK HOLD COMMAND
         ELSE
           TKAREF = TK
           PHCTKH = 0.
*
*        END OF TRACK HOLD MODE
         ENDIF
*
```

```
*
****** ROLL RATE COMMAND CONTROL LAW **************
*
***   DETERMINE REFERENCE ROLL ANGLE  AND LIMIT IT
         IF (RCWOD) PHIREF = PHIDEG + PHDOT * GRLEAD
         IF (AUTO)  PHIREF = TABLE(136)
         PHIREF = XLIM (PHIREF, -PHREFL, PHREFL)
*
***   ROLL ANGLE ERROR
         PHICE = PHIREF - PHIDEG
*
***   ROLL RATE COMMAND
         PHIDTC = GPPH * PHICE
         IF (RCWOD) PHIDTC = WHLINP
*
***   LIMIT ROLL RATE COMMAND TO LIMIT ROLL ANGLE
         IF (PHIDEG.GT.PHREFL .AND. PHIDTC.GT.0.)
      &       PHIDTC = WHLINP + PHREFL - PHIDEG
         IF (PHIDEG.LT.-PHREFL .AND. PHIDTC.LT.0.)
      &       PHIDTC = WHLINP - PHREFL - PHIDEG
*
***   ROLL RATE COMMAND TO RESPOND TO AUTOPILOT INPUT
         IF (AUTO) PHIDTC = XLIM (GPPH * PHICE, -GPLA, GPLA)
*
***   VARY GAIN TO COMPENSATE FOR AILERON EFFECTIVITY
         GPWH = GPW1 + GPW2*FLAPS + GPW3*IAS
*
***   AILERON COMMAND
         AILCMD = GDAP * (GPWH * PHIDTC - GPHD*PHDOT) / (QBAR + 10.)
*
***   IF NO ROLL RATE FEEDBACK  SWITCH TO DIRECT GAIN
         IF (GPHD.EQ.0.) AILCMD = GAWH * WHLINP
*
```

```
*
****** RUDDER COMMAND *******
*
***   RUDDER FOR TURN COORDINATION
         RCOORD = GDRB * BETADEG + GDRR * (RBDEG - GXD2R * SINPHI / VGS)
     &               + GDRDA * FLAPS * DELA
*
***   TOTAL RUDDER COMMAND
         RUDCMD = YK1P * PEDAL + RCOORD * GDRQ / (QBAR + 10.)
*
***   IF WEIGHT ON WHEELS  SWITCH TO DIRECT RUDDER CONTROL
         IF (SQUISH) RUDCMD = YK1P * PEDAL
*
****** SPOILER COMMAND ********
*
****** SERVO DRIVEN SPOILERS SELECTED
         IF (LOGIC(59) ) THEN
*
***   AILERON REQUESTED
         AILREQ = AILCMD
*
***   ZERO SPOILER COMMANDS
         DSPL = 0.
         DSPR = 0.
*
***   MAXIMUM ALLOWABLE SPOILER DEFLECTION
         SPMAX = 20. - .25 * FLAPS
*
***   RIGHT AND LEFT SPOILER DEFLECTIONS TO ASSIST AILERONS
         IF (AILREQ.GT. 5.) DSPR = XLIM( AILREQ-5., 0., SPMAX)
         IF (AILREQ.LT.-5.) DSPL = XLIM(-AILREQ-5., 0., SPMAX)
*
***   ADD SYMMETRICAL SPOILER DEFLECTION  TO GET TOTAL SPOILER CMD
         DSPR = XLIM (DSPR + SBC, 0., 40.)
         DSPL = XLIM (DSPL + SBC, 0., 40.)
*
****** END OF SERVO DRIVEN SPOILERS
         ENDIF
*
******   END  IF (LOGIC (58) ) ******************************************
         ENDIF
```

REFERENCES

1. Foulkes, Robert H., Jr, "Control Augmentation for Lateral Control Wheel Steering", NASA CR-164664, Youngstown State University, 13 Aug 1981

2. Smith, Jon M., "Mathematical Modeling and Digital Simulation For Engineers and Scientists", John Wiley & Sons, 1977

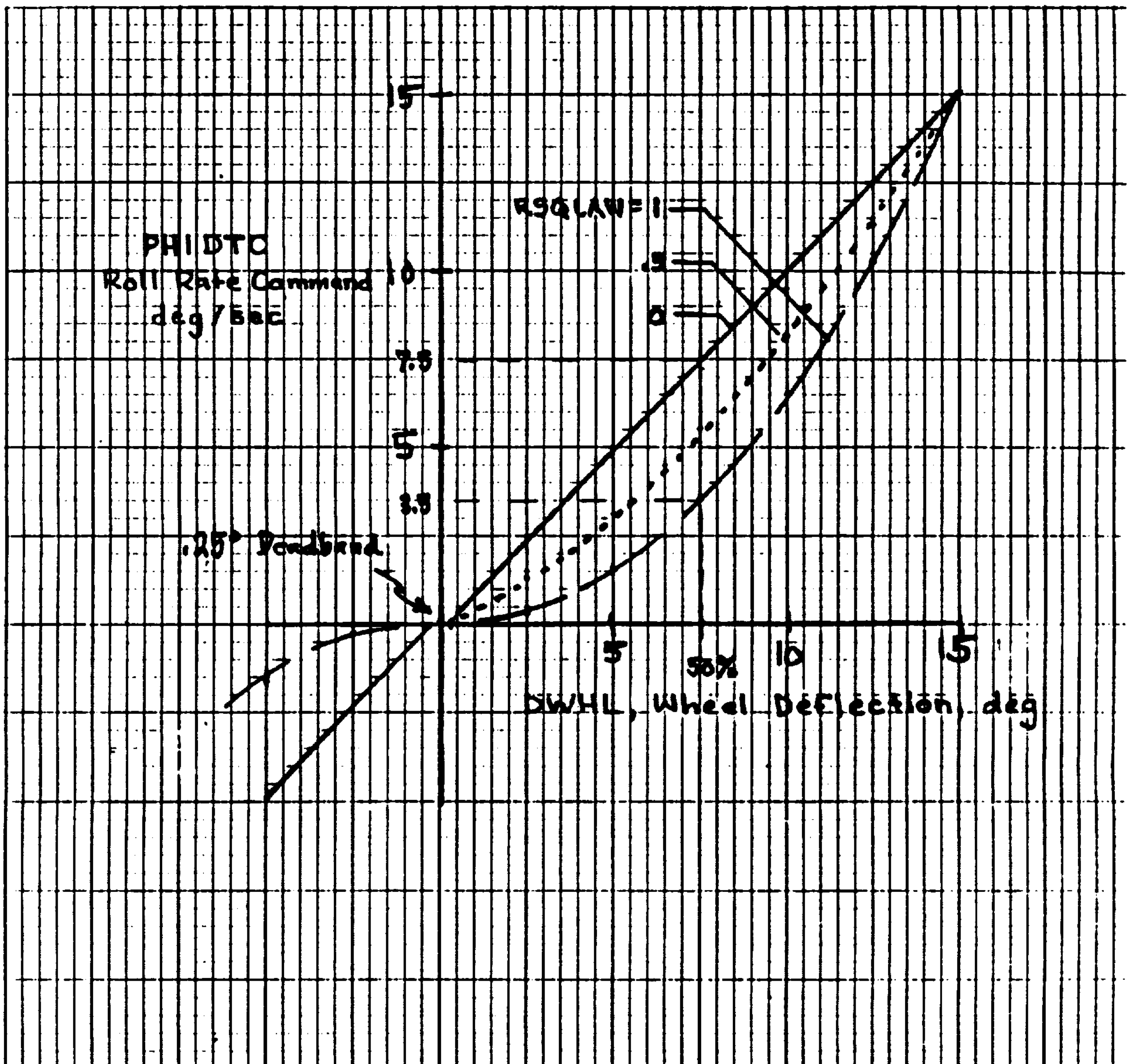


Figure 1. Roll rate command versus wheel deflection shaping function

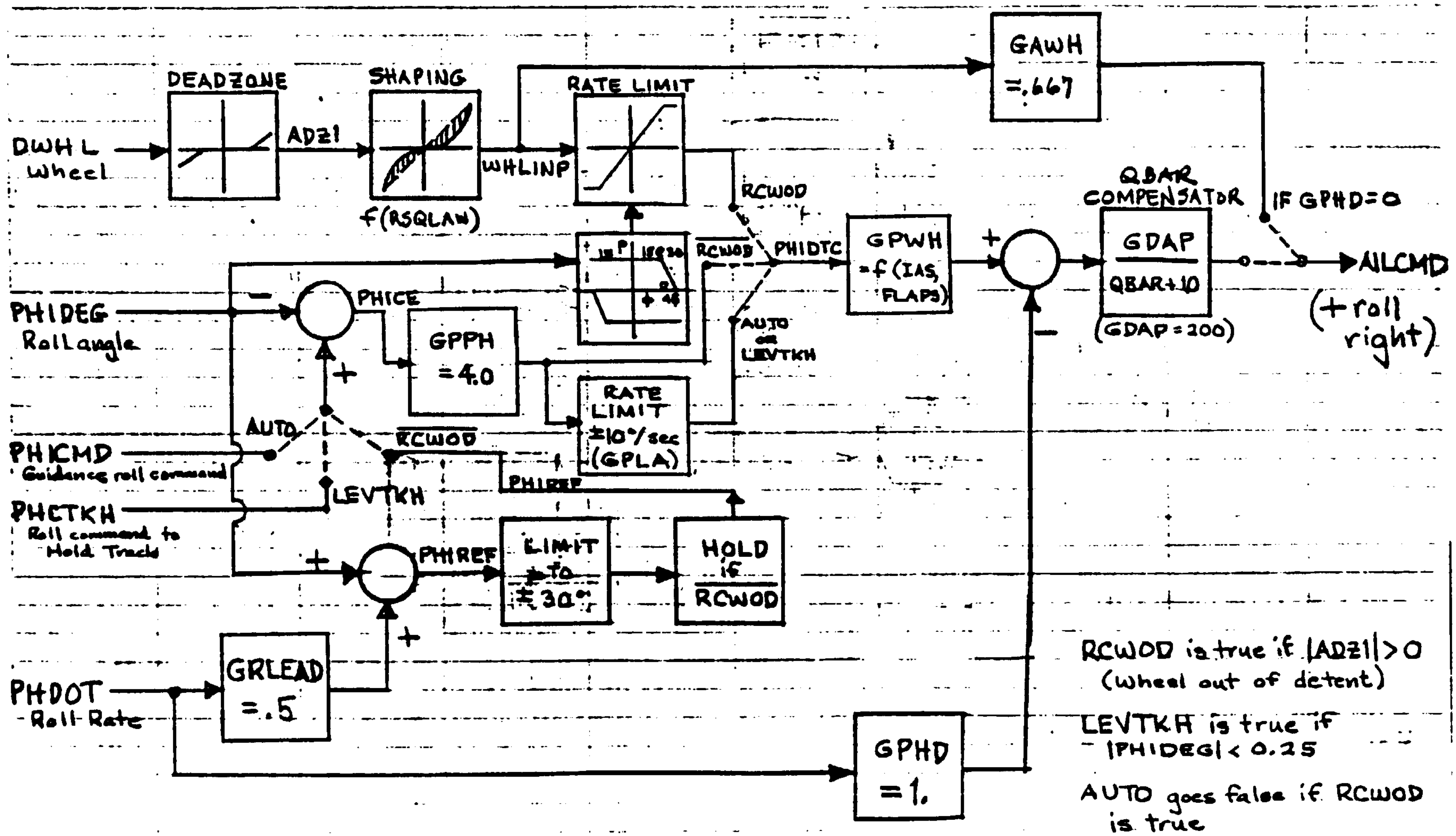


Figure 2.-LCWS E aileron control law

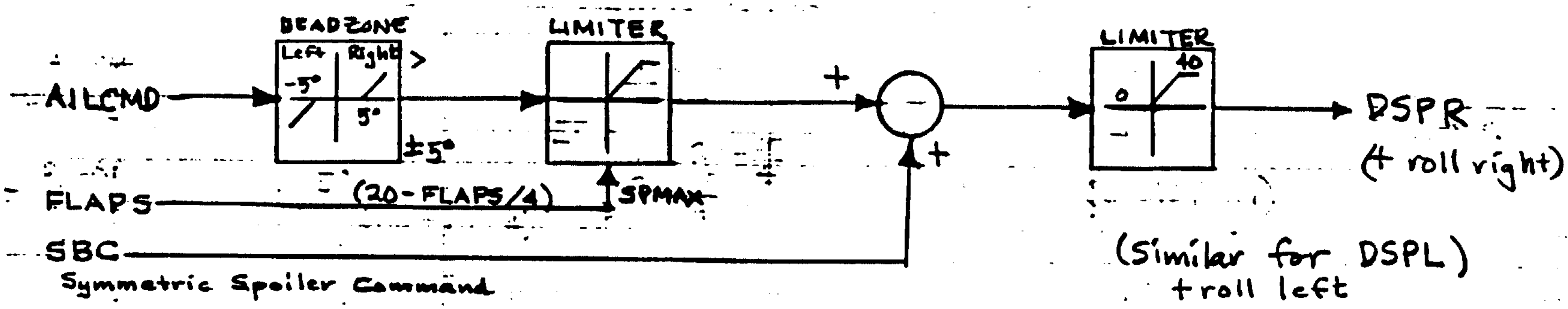


Figure 3. – LCWS E spoiler control law

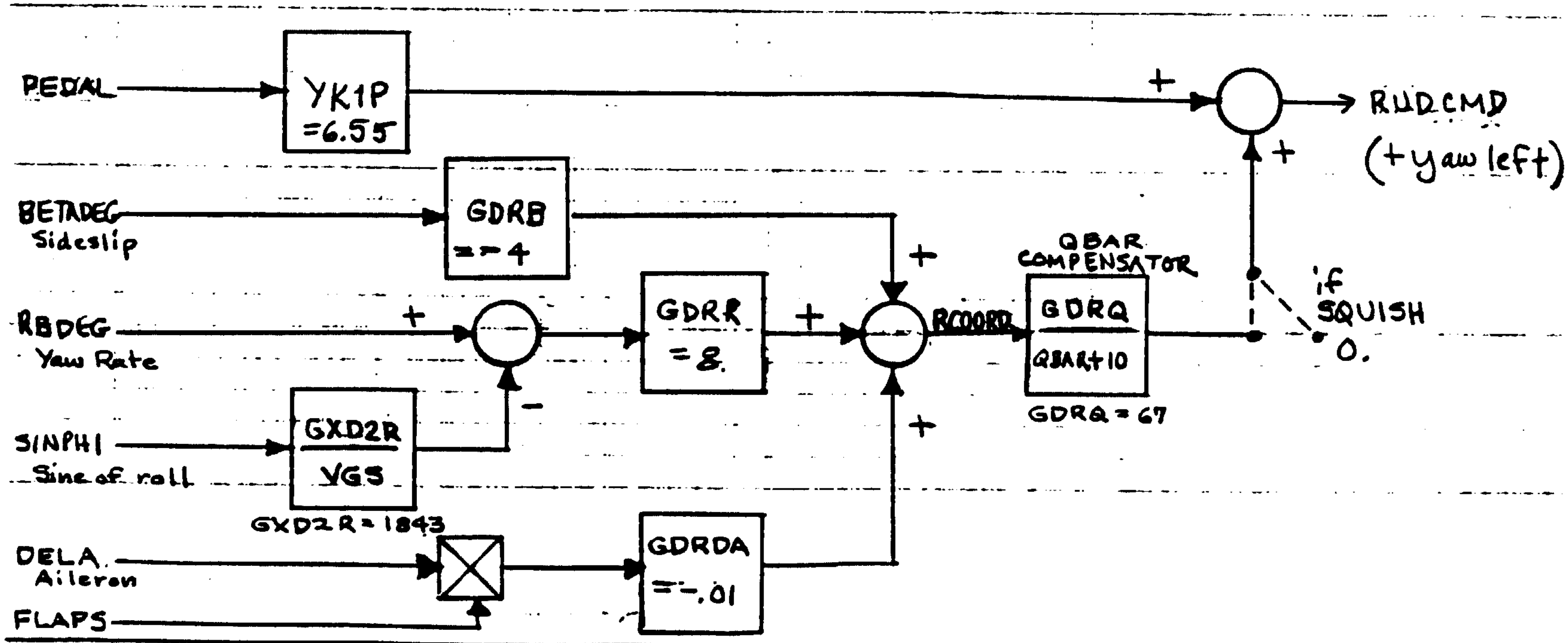


Figure 4.- LCWS E rudder control law

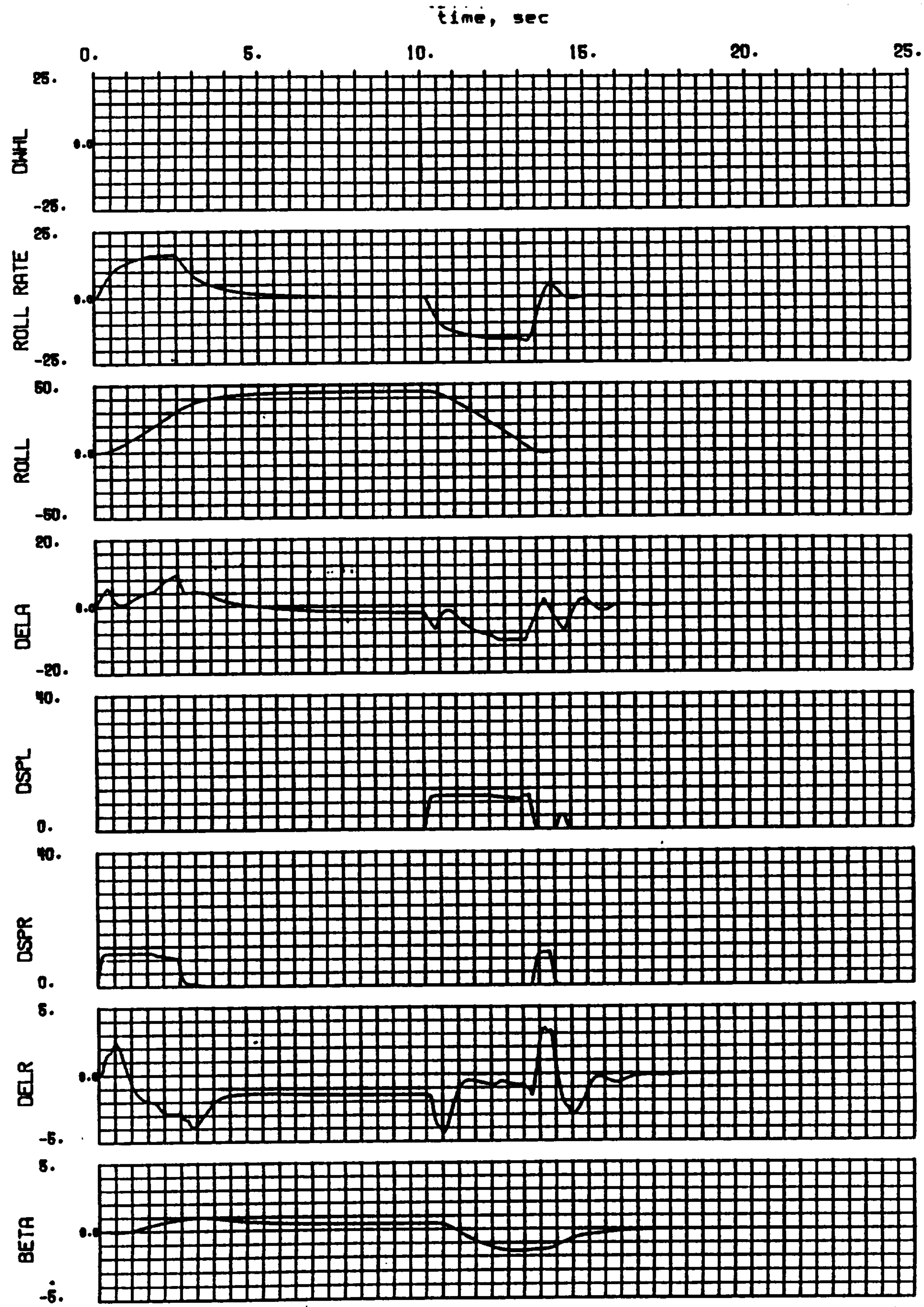


Figure 5.- Roll response: 130 knots, 40 deg flaps and gear down.

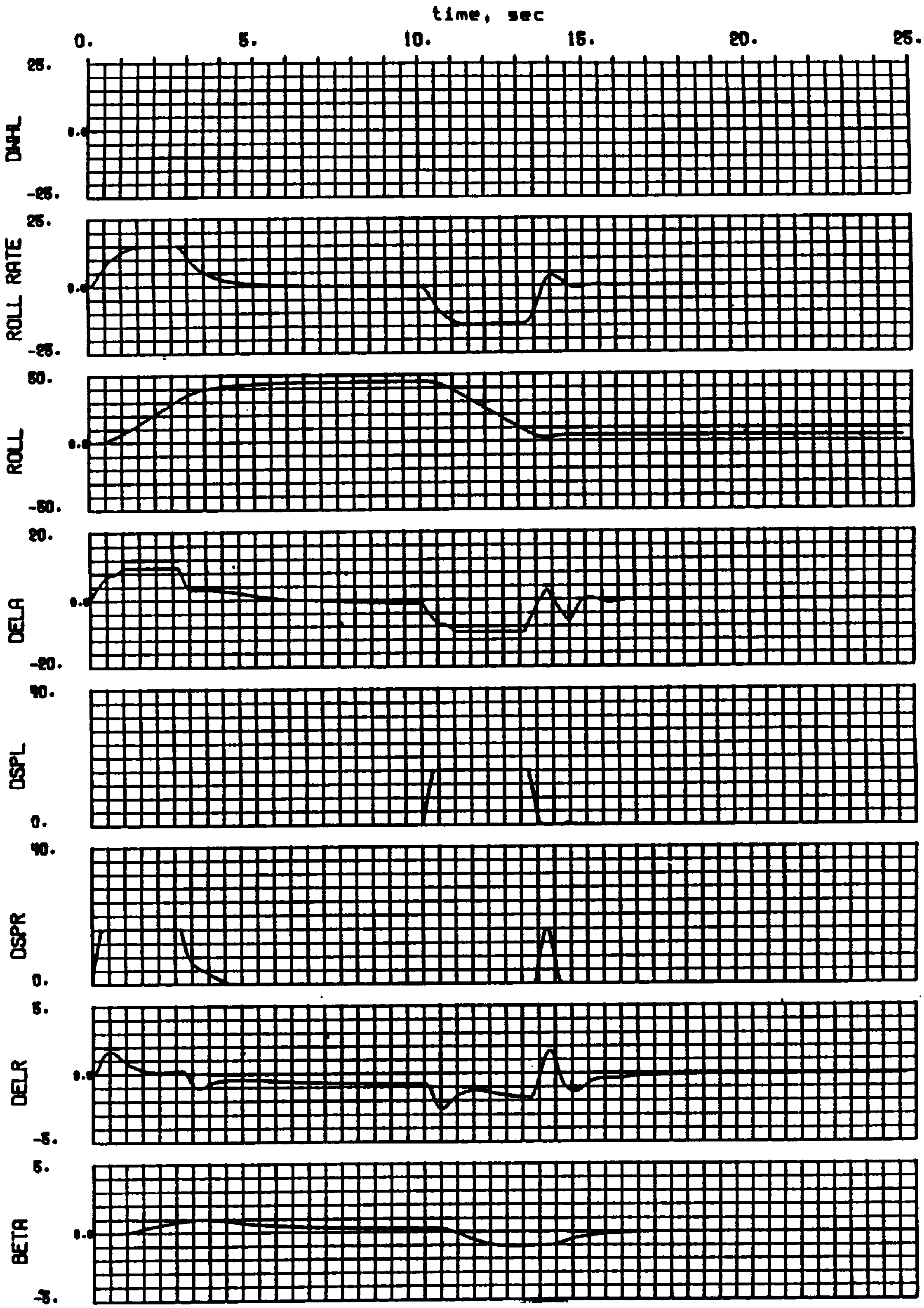


Figure 6.- Roll response: 170 knots, 15 deg flaps and gear down.

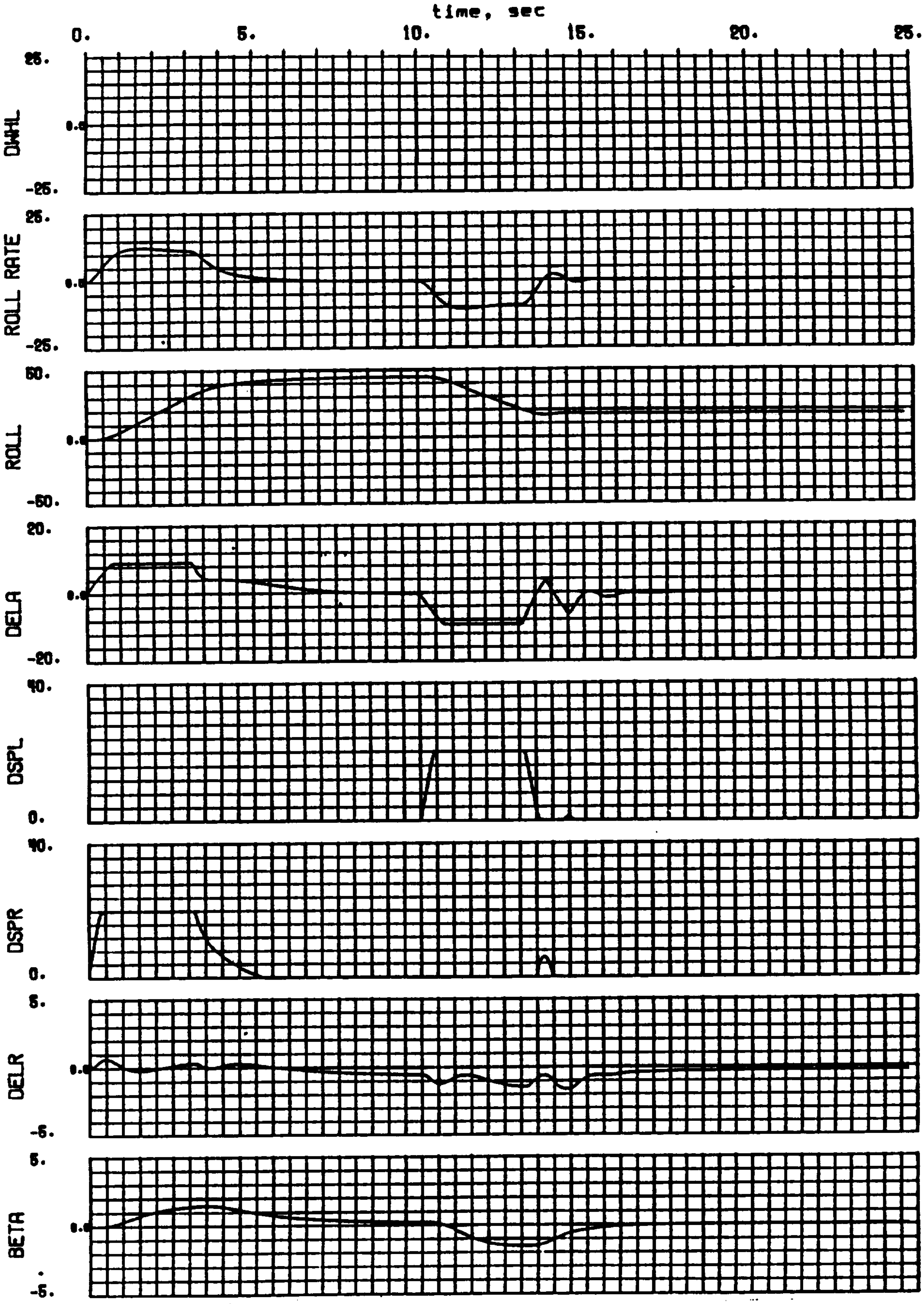


Figure 7.- Roll response: 200 knots, flaps up and gear up.

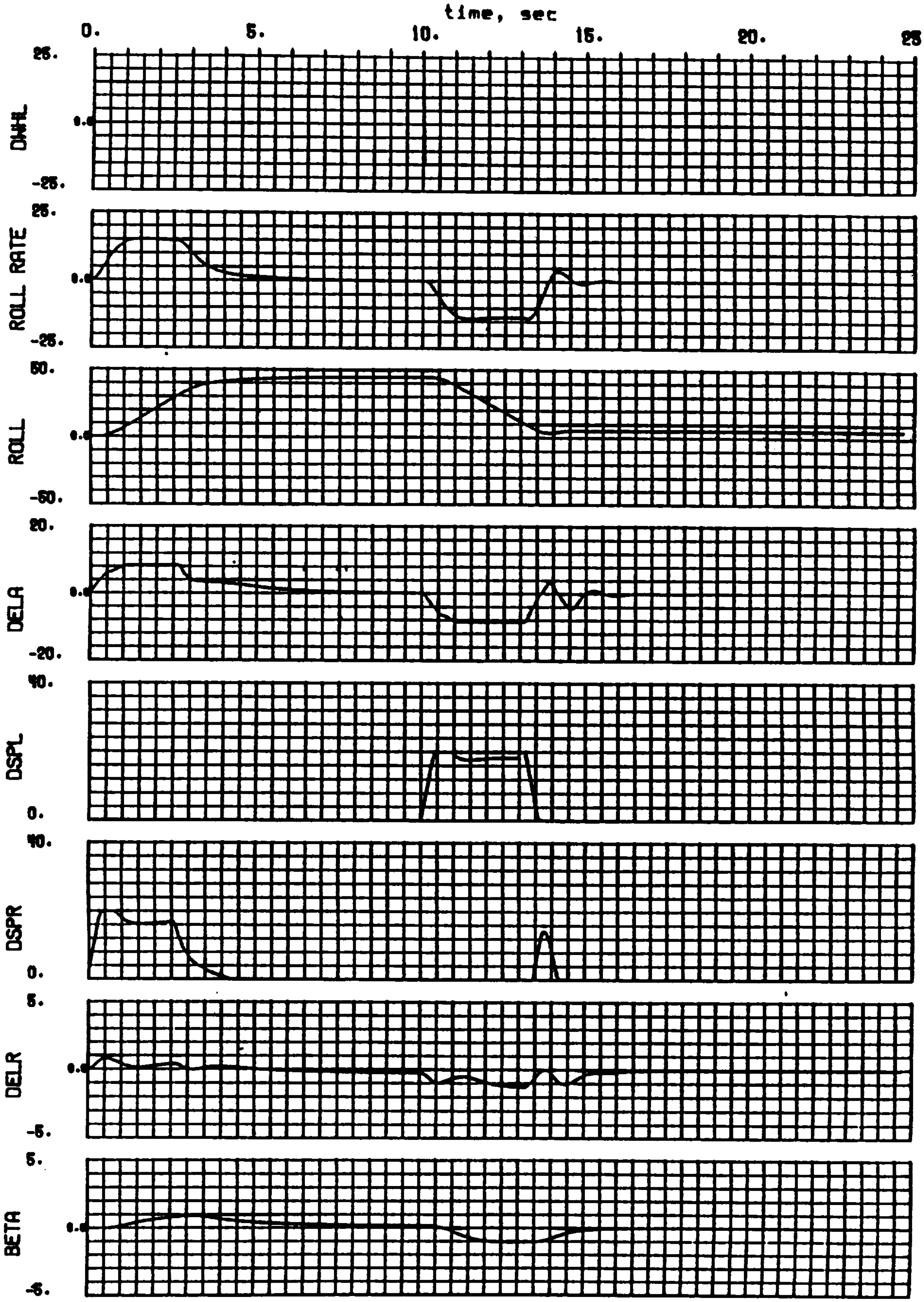


Figure 8.- Roll response: 250 knots, flaps up and gear up.

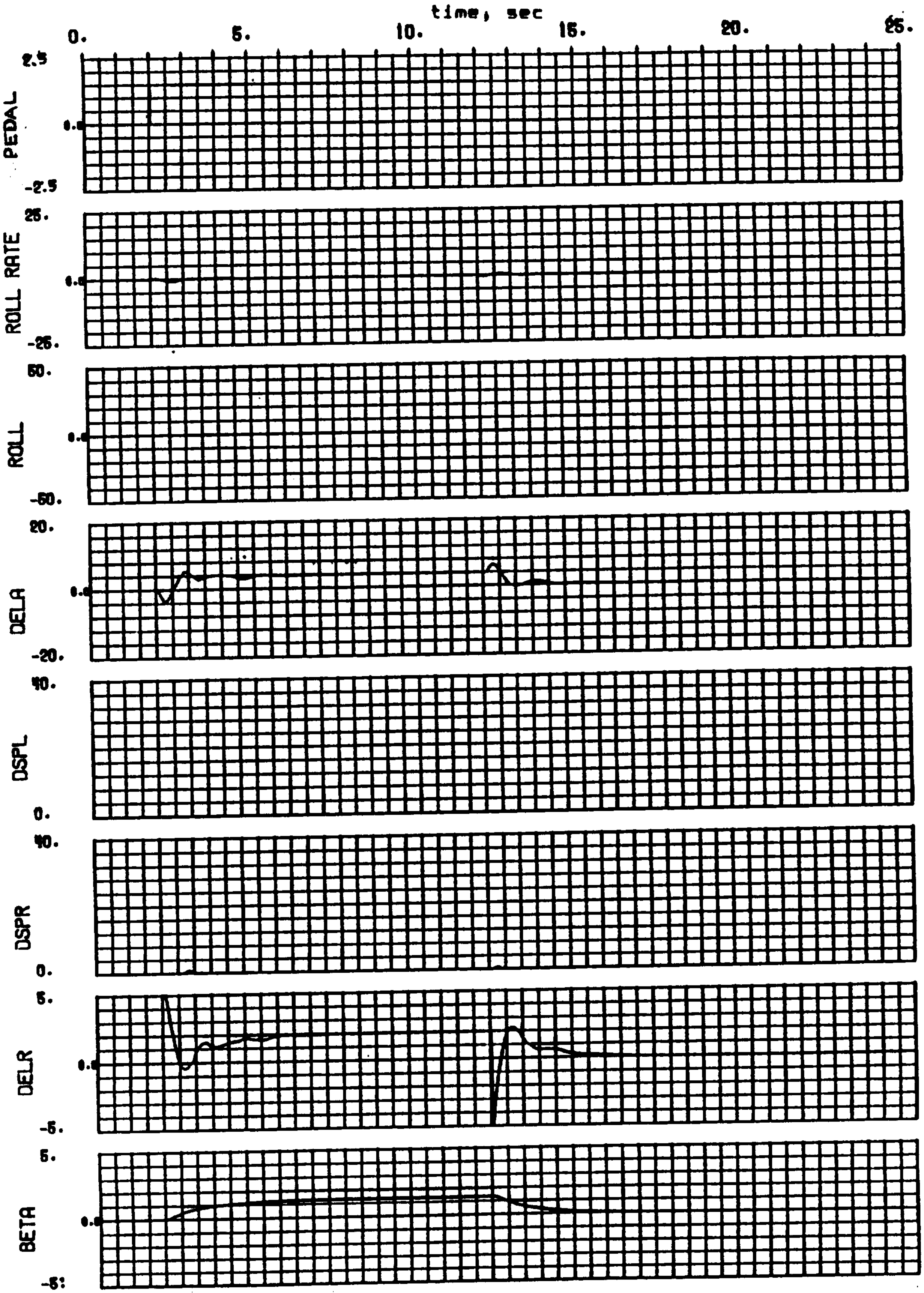


Figure 9.- Wings-level crab: 130 knots, 40 deg flaps and gear down.

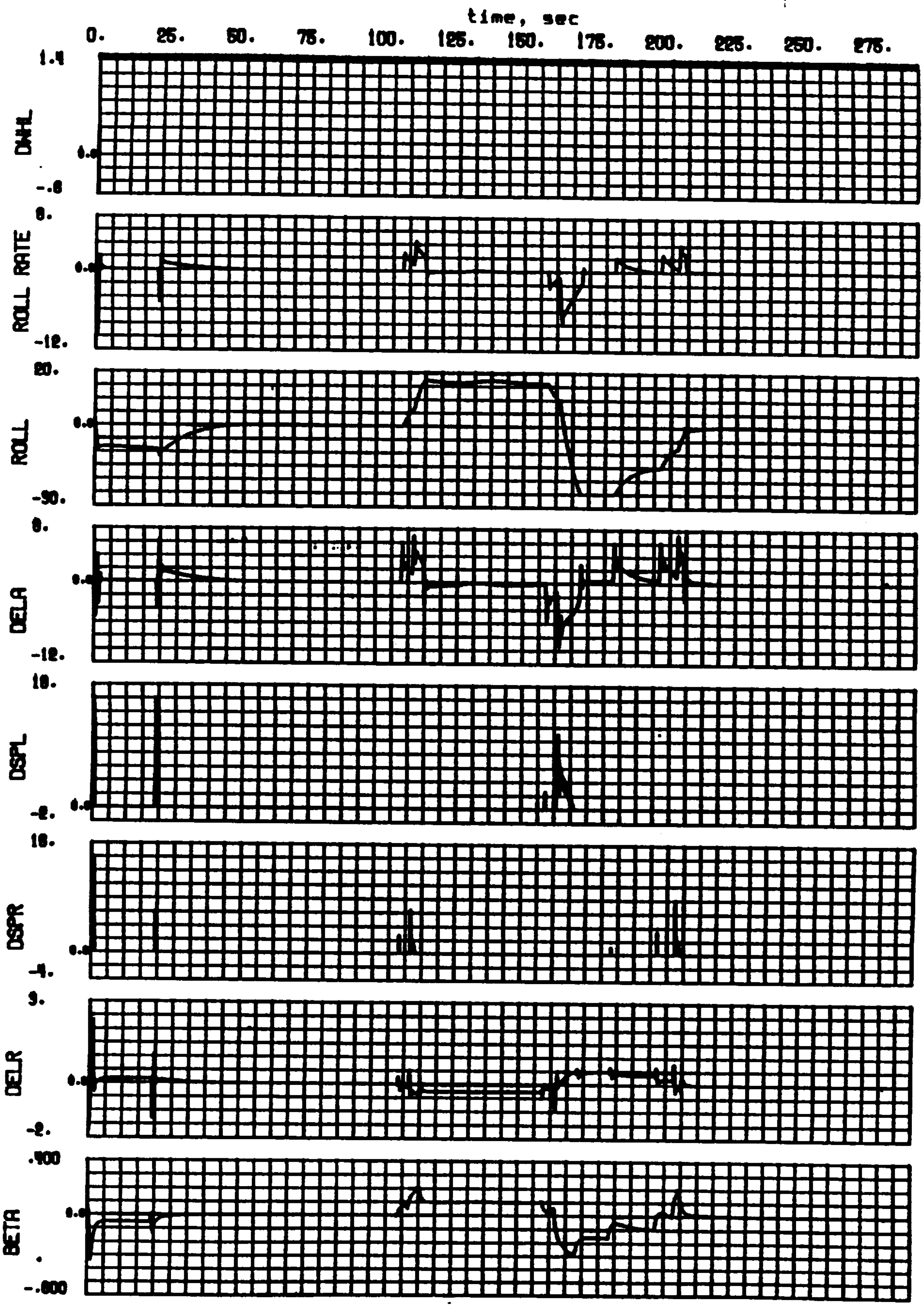


Figure 10.- MLS autoland time history.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1992

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
An Improved Lateral Control Wheel Steering Law for the Transport Systems Research Vehicle (TSRV)

5. FUNDING NUMBERS
C NAS1-19119
WU 505-64-13

6. AUTHOR(S)
W. A. Ragsdale

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Unisys Corporation
105 Research Drive
Hampton, Virginia 23666-1340

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665-5225

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-189602

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Randall D. Grove

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 60

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A lateral control wheel steering law with improved performance was developed for the Transport Systems Research Vehicle (TSRV) simulation and used in the Microwave Landing System research project. The control law converted rotational hand controller inputs into roll rate commands, manipulated ailerons, spoilers, and the rudder to achieve the desired roll rates. The system included automatic turn coordination, track angle hold, and autopilot/autoland modes. The resulting control law produced faster roll rates (15 deg/sec), quicker response to command reversals, and safer bank angle limits, while using more concise program code.

14. SUBJECT TERMS
Control Wheel Steering; Flight Control System

15. NUMBER OF PAGES
36

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		