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TURN CONTROL
OF SUBMERGED VEHICLES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Rapid turn, by application of hard rudder by the pilot, is usually accompanied by large roll and pitch excursions, and loss of depth. A coordinated-control strategy is developed which eliminates or greatly reduces these undesirable side effects. Preliminary work is also presented on a nonlinear-feedback implementation.

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I. INTRODUCTION

The equations of motion of underwater vehicles are highly nonlinear [1]-[3] differential equations, derived from Newtonian mechanics, which mathematically describe the hydrodynamic and flight characteristic of submersibles. It has been the practice of engineers to use these equations to study the hydrodynamic forces acting on the vehicle, with the aim of improving its design and handling characteristics. In the critical nonlinear regions, characterized by high angle of attack and side-slip at high speed, the vehicle motion is high coupled (lateral to longitudinal) and is very difficult to analyze. Significant insight into the vehicle's behavior can be obtained by displaying the time history of each hydrodynamic term, which collectively produce the total force and moment acting on the vehicle from instant to instant. In many cases of interest, for a particular maneuver (e.g., depth change, or turn), only a few of these terms tend to dominate. The engineer is then able to deemphasize the remainder of the terms so that he can concentrate on the few dominant ones with which he can more easily deal. In this report, it is shown how these time-history displays aid the analysis[4] of a vehicle which possesses adverse depth and roll transients in a maneuver, say a hard turn. This analysis leads to a new control strategy which markedly improves the vehicle's performance.

An empirical-experimental study of the turn control problem is also presented which confirms the effectiveness of the new turn control strategy. A possible implementation using both linear and nonlinear (relay) actuation [5] is given. Also included is a study of manual strategies used in the past where the pilot had to compromise between rapidity of the turn and adverse roll and depth.

II. PILOTED RUDDER MANEUVERS

In evasive underwater maneuvers, there is a need for performing rapid turns while keeping roll, pitch, and depth of the vehicle as stable as possible. In an attempt to imitate the rudder maneuvers initiated by a pilot when such evasive action is required, 3 different rudder commands are selected. These are

$$MAN_1(t) = 3.5 * t$$
$$MAN_2(t) = 0.35 * t^2$$
$$MAN_3(t) = 0.035 * t^3$$

and are shown in Fig. 1, 2 and 3.

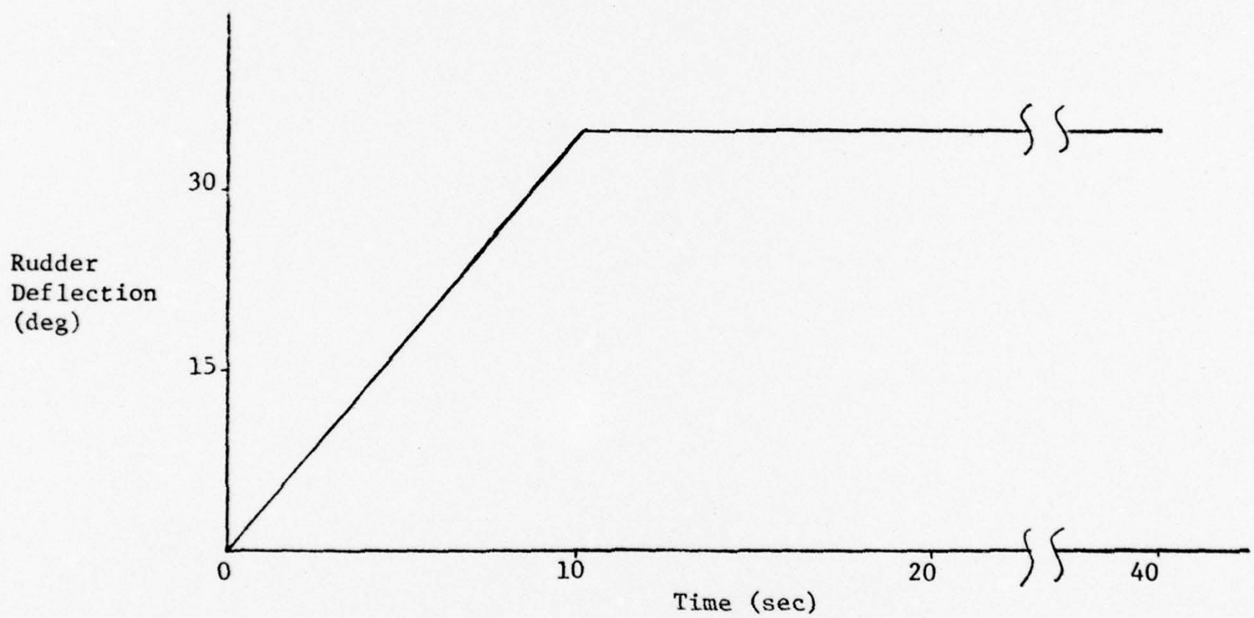


Fig. 1. $MAN_1 = 3.5 * t$

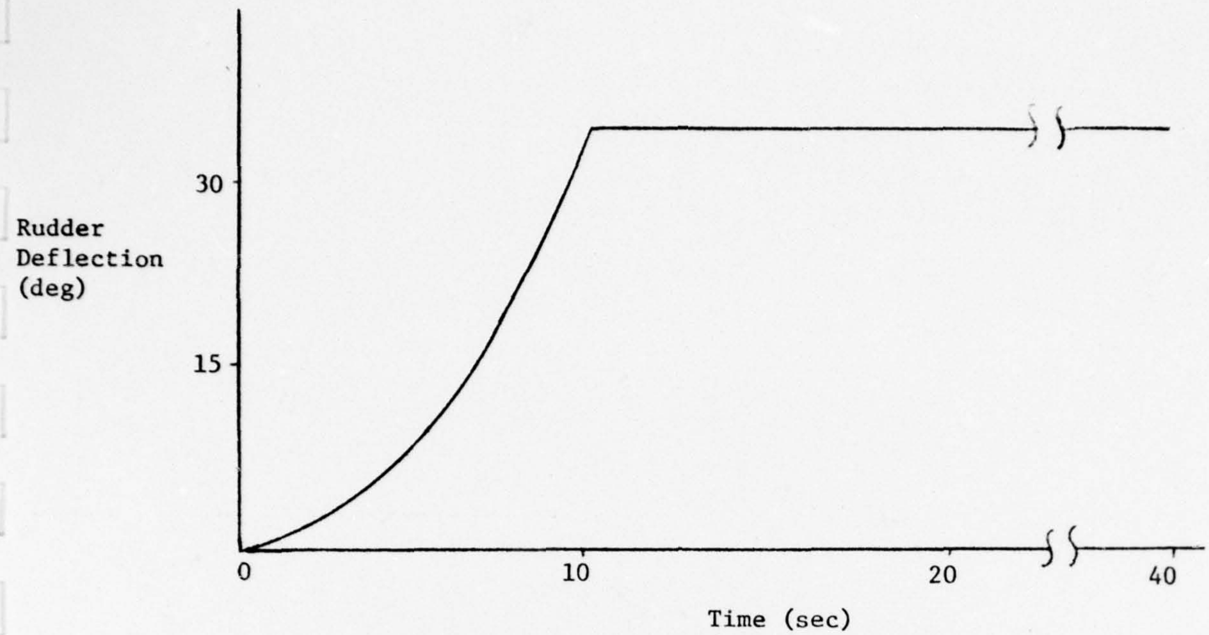


Fig. 2. $MAN_2 = 03.5 * t^2$

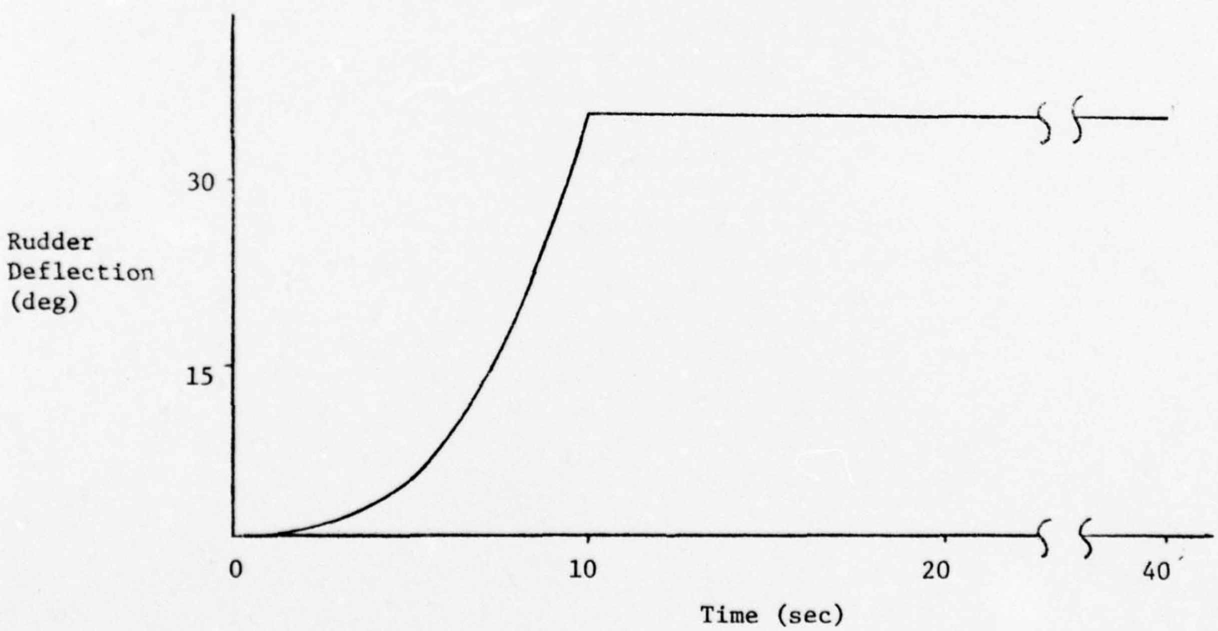


Fig. 3. $MAN_3 = 0.035 * t^3$

Computer runs were made with these rudder commands for two cases: (a) forward speed U_o held constant, say, by means of a cruise control system, and (b) forward speed varying in the absence of a cruise control system. Also these runs are made both in the presence and the absence of LLCS, i.e., linear longitudinal control system (existing in the NCSC Trajectory program). For the case where the LLCS is a comparison of the vehicle response between the vehicle response with and without cruise control is given in Table 1.

Table 1

Vehicle Responses with LLCS Off

1a

With Cruise Control ($U_o \equiv$ Const.)

	Time of 180° Turn (sec)	Max Roll (deg)	Max Pitch (deg)	Max Depth (deg)
$MAN_1(t)$	13.2	-53.1	-71.9	415.6
$MAN_2(t)$	14.8	-58.7	-69.0	395.1
$MAN_3(t)$	15.6	-61.8	-75.8	385.8

1b

Without Cruise Control

	Time of 180° Turn (sec)	Max Roll (deg)	Max Pitch (deg)	Max Depth (deg)
$MAN_1(t)$	16.6	-28.9	-25.3	116.5
$MAN_2(t)$	18.4	-31.9	-27.9	116.9
$MAN_3(t)$	19.8	-36.6	-25.7	72.4

It can be seen from Table 1 that although the 180° turn is executed slightly faster when the speed is held constant, the values of the maximum roll, pitch and depth are much larger than for the case where the speed is not held constant. In particular, the maximum is nearly twice as much as for the case where cruise control is not utilized. We believe a slightly slower turning time with greatly enhanced response stability is a good tradeoff. In the remaining investigation, therefore, we will cruise contról is turned off during rapid turn maneuvers.

Next we examine the performance of the vehicle for these pilot rudder commands in the presence of LLCS, the linear longitudinal control system (existing in the routine AUTO of the NCSC trajectory program). The results are given in Table 2.

Table 2

Responses of Vehicle to Rudder Maneuvers When Linear Control System is Activated

MAN_i	Time of 180° Turn (sec)	Max Roll (deg)	Max Pitch (deg)	Max Depth (feet)	Final Roll (deg)	Final Pitch (deg)
MAN_1	16.8	-29.3	-21.4	70.2	-16.6	-3.2
MAN_2	18.6	-32.3	-24.6	71.6	-16.6	-3.4
MAN_3	19.8	-36.6	-26.4	72.4	-16.6	-3.5

From a comparison of Tables 2 and 1b it is concluded that the existing linear longitudinal control system does not adequately reduce the adverse roll, pitch and depth-change during a piloted turn. This points to the need for better coordinated control during rapid-turn maneuvers. In Chapter III we will deal with this problem extensively. However, let us point out that among the three pilot commands, $MAN_1(t)$ not only leads to a faster turn-around time, but also the values of maxiumum roll, pitch and depth change are slighter better than for $MAN_2(t)$ and $MAN_3(t)$.

The most stable and fastest turn maneuver, $MAN_1(t)$, is thus seen to be the best suited pilot maneuver for evasive operations. For this pilot command, the rapidity of the turn can be increased by reducing the duration of the ramp, but of course at the expense of stability of the turn. In the extreme case, this command becomes the same as the step command ($\delta_r \equiv +35^o$) for which the 180^o turn can be performed in 14.0 seconds. This is accompanied by a maximum roll of -43.7°; see Table 3 for the performance under a step rudder command.

Table 3

Vehicle Response to Hard Rudder ($\delta_r = +35^o$ step)

$U_o \neq$ constant; LLCS utilized

Time (sec)	Speed (ft/sec)	Pitch (deg)	Depth (feet)	Roll (deg)	Heading (deg)
0	8.7	0	0	0	0
1	8.2	0.1	0	2.3	-9.5
2	7.3	0.1	0	10.7	-27.0
3	6.5	-2.6	0.1	-43.1	-52.5
3.8	6.0	-7.3	0.5	-43.7	-55.2
4	5.9	-8.8	0.6	-43.4	-57.8
5	5.5	-15.9	2.2	-34.2	-70.5
6	5.2	-21.0	4.7	-21.7	-84.0
7	5.0	-22.8	7.9	-16.3	-98.0
8	4.8	-22.4	11.4	-18.2	-111.4
9	4.7	-21.4	14.8	-17.8	-124.0
10	4.7	-20.7	18.1	-15.7	-136.2
.	.	.	.	.	.
.	.	.	.	.	.
13.6	4.5	-18.1	28.7	-16.1	-179.6
.	.	.	.	.	.
.	.	.	.	.	.
20	4.4	-15.1	43.8	-16.4	-256.1
.	.	.	.	.	.
.	.	.	.	.	.
40	4.3	-7.9	72.4	-15.6	-488.1

III. EFFECT OF K_v AND K_{4T} TERMS IN HARD TURN

The vehicle considered (henceforth called USFRPV) is neutrally buoyant and equipped with three control surfaces, bow planes, stern planes and rudder with maximum deflections of 20°, 25° and 35°, respectively. Table 4 shows the time history for a maximum turn-rate maneuver where the bow and stern planes are undeflected and the rudder is at the maximum deflection of 35°. The run is made by setting XD(1) = 0 in the program and the speed is set at 8.66 ft/s. One notes the

Table 4

Turn Time Histories: Stern and Bow Plane at Zero Deflection, Rudder at 35 degrees.

Time (sec)	W (ft/sec)	V (ft/sec)	Depth (ft)	Pitch Rate q (Deg/Sec)	Pitch Angle θ (Deg)	Roll Angle ϕ (Deg)	Yaw Angle ψ (Deg)
0.0	0.0	0.0	50.00	0.0	0.0	0.0	0.0
0.5	-0.05	0.84	50.00	-10.36	-0.02	1.90	-2.84
1.0	-0.07	1.62	49.99	-15.73	0.05	2.30	-9.50
1.5	0.09	2.16	49.98	-17.81	0.19	-1.78	-18.02
2.0	0.46	2.42	49.97	-17.83	0.07	-10.68	-27.04
2.5	0.94	2.42	49.98	-16.63	-0.76	-23.22	-35.82
3.0	1.29	2.24	50.05	-15.19	-2.60	-35.36	-43.89
3.5	1.38	2.09	50.25	-14.40	-5.43	-92.44	-51.11
4.0	1.25	2.04	50.64	-14.23	-8.95	-43.36	-57.66
4.5	1.03	2.04	51.28	-14.20	-12.78	-39.80	-63.89
5.0	0.81	2.04	52.20	-14.05	-16.46	-33.63	-70.17
6.0	0.57	2.00	54.82	-13.51	-21.88	-19.61	-83.63
7.0	0.73	1.83	58.15	-12.58	-23.78	-13.35	-97.80
8.0	1.07	1.65	61.75	-11.10	-23.29	-17.21	-111.32
9.0	1.14	1.50	65.33	-10.52	-22.61	-18.44	-123.83
10.0	1.04	1.49	68.82	-10.83	-22.25	-15.84	-136.03
11.0	1.02	1.48	72.26	-10.85	-22.09	-15.66	-148.26
12.0	1.02	1.45	75.65	-10.74	-21.86	-16.33	-160.43
13.0	0.99	1.46	78.99	-10.83	-21.72	-16.09	-172.55
14.0	0.96	1.47	82.28	-10.90	-21.72	-15.99	175.28
15.0	0.96	1.47	85.56	-10.89	-21.79	-16.33	163.09
16.0	0.99	1.48	88.83	-10.91	-21.90	-16.40	150.88
17.0	0.93	1.48	92.10	-10.92	-22.66	-16.33	138.66
18.0	0.93	1.48	95.38	-10.92	-22.21	-16.35	126.43
19.0	0.93	1.48	98.68	-10.90	-22.35	-16.36	114.19

undesirable depth loss and large roll excursion. The problem is to find the hydrodynamic cause and then design a control strategy for the bow, stern and rudder planes to counter the depth and roll variations -- while still maintaining the high turn-rate. The first concern is the depth loss. Looking at a time history of the toal body-axis Z force and the toal pitch moment (right hand side of equations of motion), shown in Fig. 4, we see that depth loss does not come from the Z force (which is negative, indicating an upward force), but rather is due to a negative pitching moment which causes a delayed downward pitch angle.

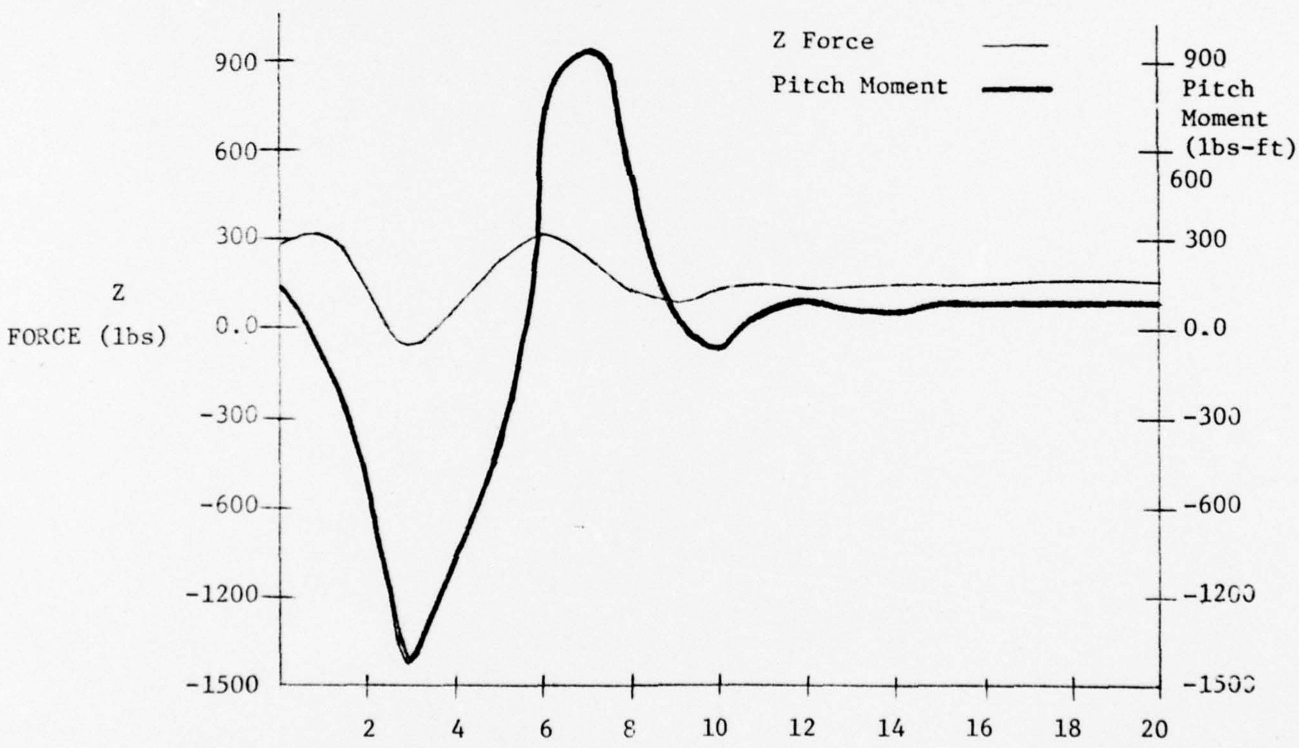


Fig. 4. Z-Force and Pitch Moment: Turn Maneuver with Zero Deflection of Stern and Bow Planes, Rudder at 35 Degrees.

The time histories in Fig.5 are a breakdown of the dominant terms which cause this negative pitching moment. The obvious fix is to use the stern planes to counter the negative moment, the bow planes to produce an upward force when the vehicle is pitched down. In general, the bow planes on this particular vehicle are marginally effective and produce only moderate Z force and pitch moment.

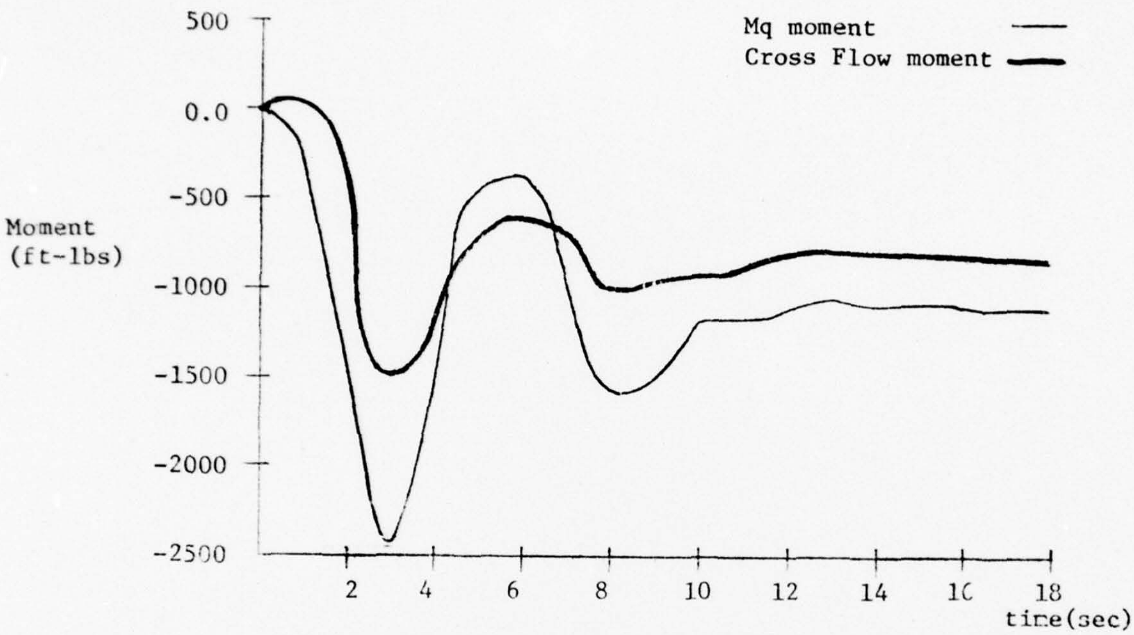


Fig. 5. Dominate Negative Pitch Moment Terms: Turn Maneuver with Zero Deflection of Stern and Bow Planes, Rudder at 35 Degrees.

Table 5 shows the turn maneuver with bow planes in maximum rise position $\delta_b = 20°$, and stern plane, δ_s, held at 10°. This combination reduces the depth excursion to an acceptable level. However, the adverse roll motion is still present. The solution to this problem is not obvious. The negative roll excursion results from the negative roll moment produced during 0.5 and 2.0 second time interval (Fig. 6).

Table 5

Turn time histories: Stern planes at -10 degrees, Bow planes at 20 degrees and rudder at 35 degrees.

Time (sec)	W (ft/sec)	V (ft/sec)	Depth (ft)	Pitch Rate q (Deg/Sec)	Pitch Angle θ (Deg)	Roll Angle ϕ (Deg)	Yaw Angle ψ (Deg)
0.0	0.0	0.0	50.00	0.0	0.0	0.0	0.0
0.5	-0.10	0.83	49.92	2.61	0.82	1.66	-2.81
1.0	-0.07	1.62	49.70	3.97	2.61	0.05	-9.38
1.5	0.21	2.14	49.25	5.85	4.50	-8.61	-17.71
2.0	0.68	2.32	48.61	7.73	5.62	-22.75	-26.60
2.5	1.07	2.24	47.87	8.31	5.34	-36.77	-35.27
3.0	1.17	2.13	47.15	7.48	3.60	-45.13	-43.28
3.5	1.06	2.08	46.57	6.04	0.83	-46.99	-50.59
4.0	0.87	2.06	46.23	4.75	-2.40	-44.37	-57.44
4.5	0.63	2.04	46.15	3.88	-5.54	-39.09	-64.16
5.0	0.53	2.00	46.32	3.45	-8.16	-32.44	-70.93
6.0	0.41	1.91	47.28	3.69	-10.97	-20.36	-84.75
7.0	0.60	1.78	48.68	5.07	-10.67	-16.89	-98.24
8.0	0.81	1.60	50.13	5.89	-8.76	-18.65	-110.82
9.0	0.82	1.52	51.41	5.41	-6.62	-17.25	-122.68
10.0	0.78	1.49	52.46	4.96	-2.63	-15.65	-134.26
11.0	0.80	1.45	53.28	4.98	-2.70	-16.10	-145.67
12.0	0.78	1.44	53.86	4.83	-0.85	-16.22	-156.97
13.0	0.79	1.45	54.20	4.57	0.77	-16.01	-168.26
14.0	0.72	1.45	54.31	4.47	2.18	-16.47	-179.60
15.0	0.70	1.46	54.22	4.38	3.39	-16.92	169.03
16.0	0.67	1.47	53.97	4.23	4.41	-17.02	157.62
17.0	0.65	1.48	53.56	4.13	5.27	-17.14	146.16
18.0	0.63	1.49	53.04	4.09	6.02	-17.53	134.66
19.0	0.62	1.49	52.40	4.03	6.69	-17.41	123.13

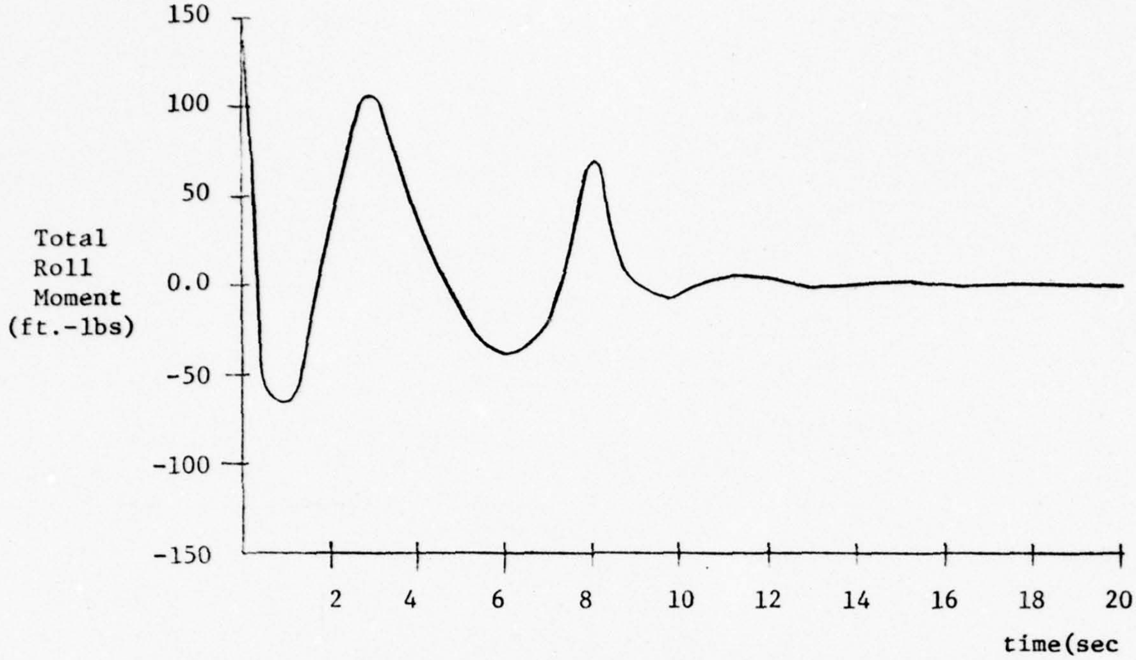


Fig. 6. Total Roll Moment: Turn Maneuver, Stern Plane at -10 Degrees, Bow Planes at 20 Degrees, and Rudder at 35 Degrees.

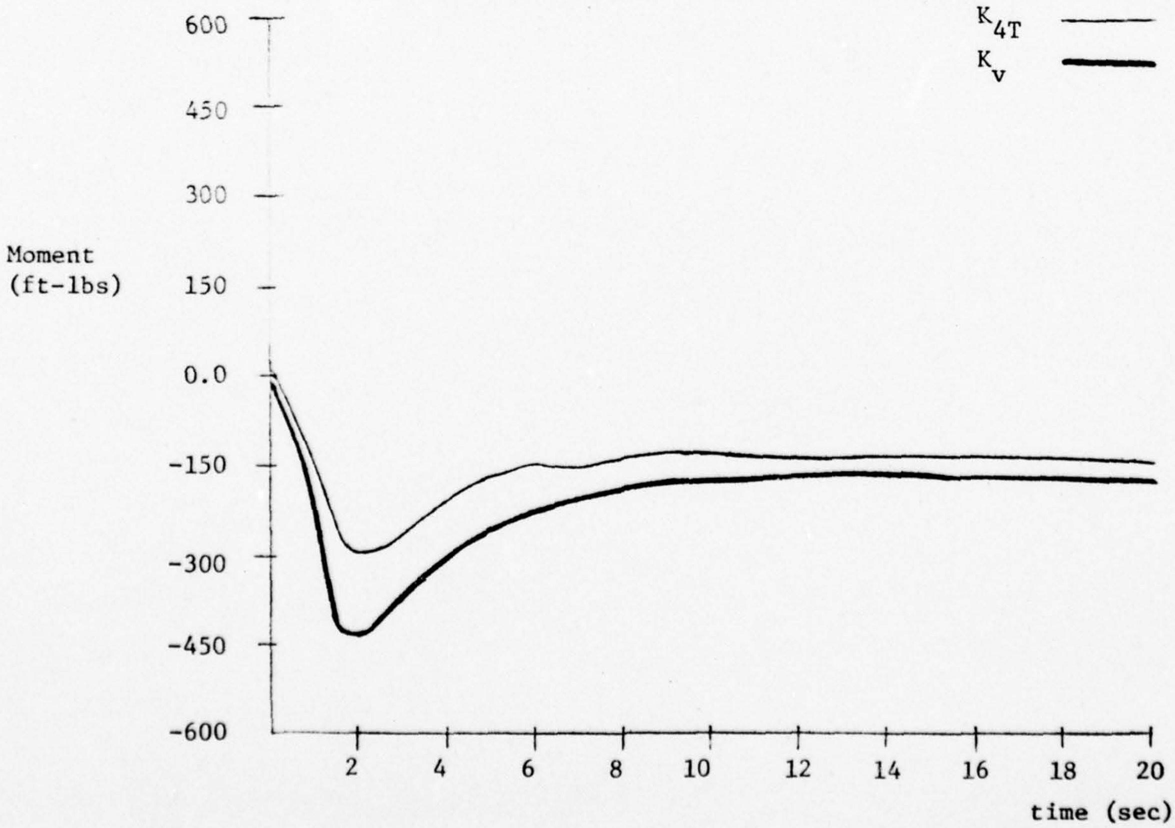


Fig. 7. K_v and K_{4T} Roll Moment Terms: Turn Maneuver, Stern Plane at -10 Degrees, Bow Plane at 20 Degrees, and Rudder at 35 Degrees.

Fig. 7 shows the two dominant terms which contribute to this negative moment. These terms are

$$K_v uv$$

and

$$K_{4T}(u^2+w_t^2+v_t^2)\left\{\tan^{-1}\left(\frac{\sqrt{w_t^2+v_t^2}}{u}\right)\right\}^2 \frac{4v_t w_t (w_t^2-v_t^2)}{(w_t^2+v_t^2)}$$

where

u = axial velocity

v = side-slip velocity

w = plunge velocity

q = pitch rate

r = yaw rate

x_{tail} = distance from center of mass to tail (negative value)

and

$$w_t = w - q\, x_{tail}$$

$$v_t = v + r\, x_{tail}$$

K_v is a hydrodynamic coefficient less than zero

K_{4T} is a hydrodynamic coefficient greater than zero

Because the turn is to the left (yaw rate negative), v will be generally negative. One could reduce the effect of the K_v term by reducing the rudder deflection, thereby reducing v. But this is undesirable since it would lead to a concurrent reduction in turn rate. However, the second term offers an alternative solution. In the turn (Table 5) one observes that

$$w_t > 0$$

$$v_t > 0$$

$$v_t^2 > w_t^2$$

It is possible to reverse the first relation while maintaining the second and third which would create a positive roll moment with the K_{4T} term. Clearly, a negative w_t exists if the vehicle is pitched down to fly at a negative angle of attack. This can be obtained by deflecting the stern plane to a dive position. Because there is a larger time lag between the stern plane deflection and depth response than between the stern plane deflection and pitch response, there will be an appreciable length of time, right after the planes are deflected, where the vehicle is pitched down undergoing little depth change, and thus producing the desired negative w_t. If this interval encompasses the adverse roll region, then it would be possible to use this control strategy to alleviate the large roll excursions. The stern plane must soon be sent to a rise position so that significant depth change does not accrue from the dive position. After several simulation studies, involving different magnitudes and transition rates, an acceptable stern plane strategy was devised. Table 6 shows the time histories of the vehicle's response. Fig. 8 shows the total roll moment time history for this maneuver and Fig. 9 shows the roll moment produced by the K_v and K_{4T} terms.

Table 6. New turn time histories: Bow planes at 20 degrees and rudder at 35 degrees.

Time (sec)	W (ft/sec)	V (ft/sec)	Depth (ft)	Pitch Rate, q (deg/sec)	Pitch θ (deg)	Roll Angle, ϕ (deg)	Yaw Angle, ψ (deg)	S. Pln. Defl., δs (deg)
0.0	0.0	0.0	50.00	0.00	0.00	0.00	0.00	0.00
0.5	-0.35	0.83	49.91	-0.32	0.11	1.92	-2.82	10.42
1.0	-0.76	1.56	49.67	-2.45	-0.23	3.44	-9.45	20.83
1.5	-1.12	2.03	49.34	-4.32	-1.42	4.40	-17.83	25.00
2.0	-1.33	2.25	49.05	-4.80	-2.93	6.23	-26.73	25.00
2.5	-1.40	2.32	48.87	-4.52	-4.16	8.60	-35.54	25.00
3.0	-1.34	2.34	48.79	-3.80	-4.85	10.49	-44.03	25.00
3.5	-1.21	2.34	48.80	-2.94	-5.01	11.16	-52.11	25.00
4.0	-1.01	2.33	48.86	-2.11	-4.83	10.24	-59.75	25.00
4.5	-0.78	2.31	48.95	-1.31	-4.54	7.66	-67.00	23.60
5.0	-0.54	2.27	49.05	-0.55	-4.31	3.61	-73.90	22.20
6.0	-0.09	2.13	49.29	0.59	-4.55	-6.67	-86.79	19.40
7.0	0.12	1.95	49.62	0.84	-6.00	-13.81	-98.77	16.60
8.0	0.06	1.82	50.16	0.33	-8.21	-12.83	-110.28	13.80
9.0	-0.06	1.75	50.99	0.10	-10.07	-6.99	-121.83	11.00
10.0	-0.01	1.72	52.07	0.97	-10.66	-4.30	-133.54	8.20
11.0	0.25	1.69	53.28	2.53	-10.12	-8.98	-145.14	5.40
12.0	0.47	1.61	54.47	3.45	-9.47	-16.04	-156.49	2.60
13.0	0.49	1.56	55.61	3.23	-9.38	-17.78	-167.71	-0.20
14.0	0.43	1.56	56.78	2.96	-9.58	-15.58	-179.07	-3.00
15.0	0.45	1.56	57.94	3.30	-9.39	-14.58	169.40	-3.00
16.0	0.52	1.54	59.13	3.77	-8.76	-15.62	157.88	-3.00
17.0	0.55	1.52	60.25	3.84	-8.03	-16.34	146.44	-3.00
18.0	0.54	1.52	61.31	3.66	-7.42	-16.09	135.03	-3.00
19.0	0.53	1.52	62.29	3.59	-6.90	-15.89	123.61	-3.00

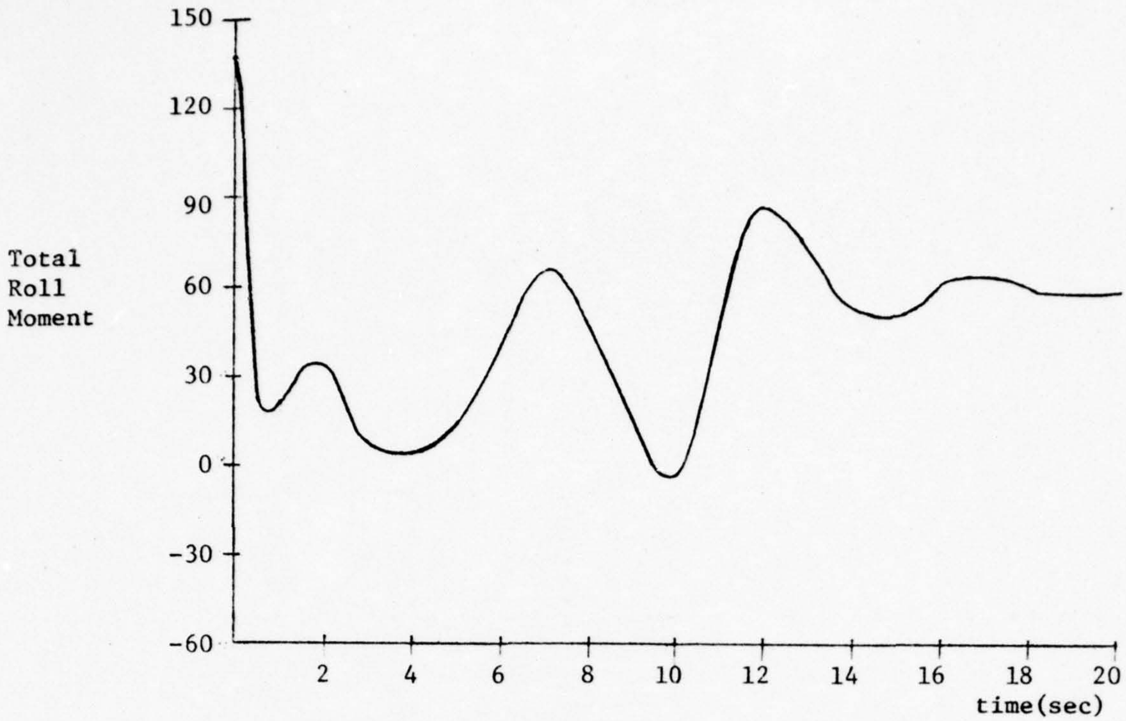


Fig. 8. Total Roll Moment: New Turn Maneuver as Described in Table 6.

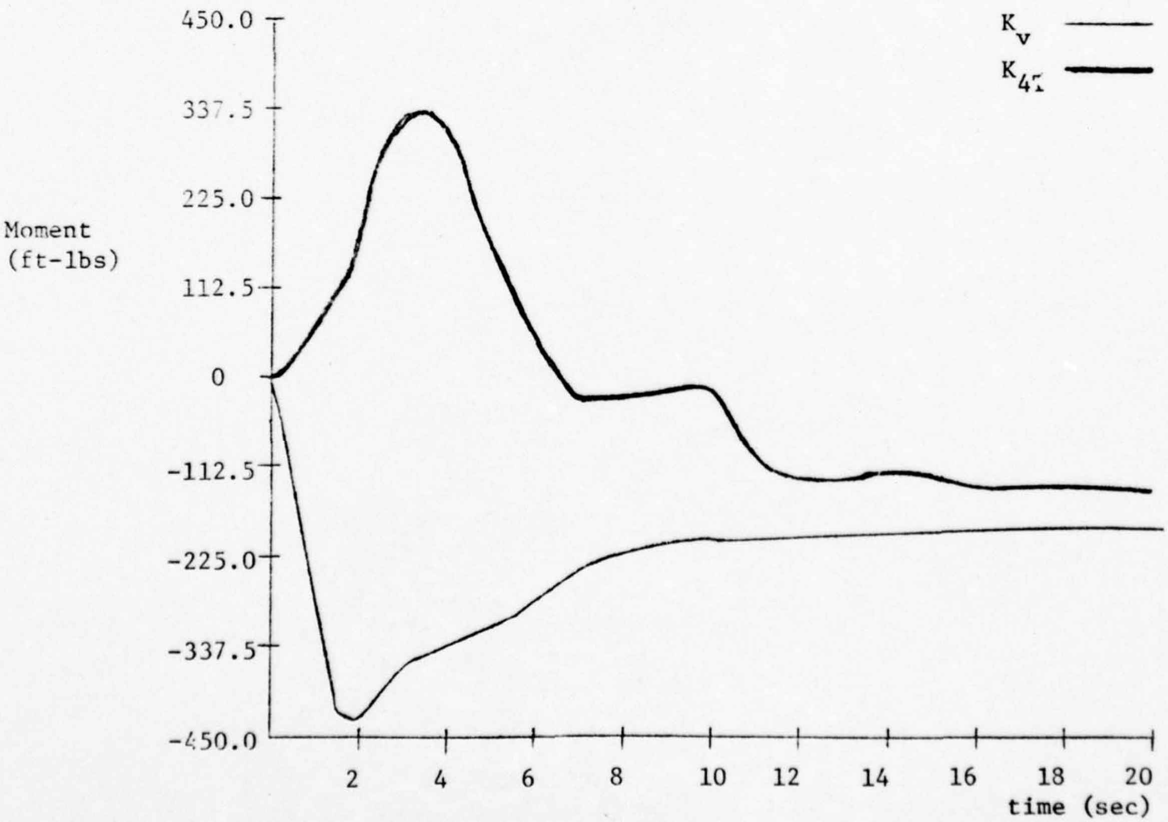


Fig. 9. K_v and K_{4T} Roll Moment Terms: New Turn Maneuver as Described in Table 6.

IV. COORDINATED TURN CONTROL SYSTEM

This section presents an empirical-experimental study of the coordinated rapid turn problem. Basically, the application of hard-rudder, (maximum amplitude step) or a slight modification thereof, will accomplish this goal. This, however, predictably results in severe excursions of roll and pitch, and loss of depth. It is therefore necessary to coordinate the bow-plane and stern-plane actions with the rudder so as to eliminate or minimize these ill-effects. In this section, a control strategy, and later a feedback system, will be developed experimentally to achieve a coordinated rapid turn. The system will be called 'TURN CONTROL SYSTEM'.

$\delta_r = 35°$: Open-Loop

The development of roll control is given in two phases. In the first phase, we seek an open loop strategy to decrease the roll, depth change, and pitch. In the second phase (page 25) we will implement the ideas of the open loop strategy into a feedback mode. Since the vehicle is slightly asymmetric, i.e., responses to positive and negative rudder are not identical, (see Table 7) the control strategy is to be found for these separately.

TABLE 7

Demonstration of Need for Separate Analysis for Positive and Negative Rudder Trajectories.

δr	Final Pitch	Final Roll	Maximum Roll	Final Depth (ft)
+35°	-23°	-16°	-44°	119
-35°	-30°	18°	48°	149

Experiments were performed, initially, to determine the effect of different bow and stern plane step-inputs upon vehicle response. A summary of some of the runs is given in Tables 8 and 9.

TABLE 8

$\delta r = +35°$ (40 second runs)

EFFECT OF BOW-PLANE ($\delta_s = 0$)

δb	Final Pitch(deg)	Final Roll(deg)	Maximum Roll(deg)	Final Depth(ft)
+10°	-16	-16	-45	83
-10°	-30	-16	-42	147
+20°	- 7	-15	-44	39
-20°	-34	-75	-39	164

EFFECT OF STERN-PLANE ($\delta_b = 0$)

δ_s	Final Pitch (deg)	Final Roll (deg)	Maximum Roll (deg)	Final Depth (ft)
-5	-9	-16	-45	78
+10	-50	-17	-34	169
-10	4	-17	-45	31
+25	-67	- 9	-19	86
-25	32	-22	-37	-86

TABLE 9

$\delta r = -35°$ (40 second runs)

EFFECT OF BOW-PLANE ($\delta_s = 0$)

δ_b	Final Pitch (deg)	Final Roll (deg)	Maximum Roll (deg)	Final Depth (ft)
+10	-22	18	49	111
-10	-37	17	47	175
+20	-16	17	49	66
-20	-42	16	44	190

EFFECT OF STERN PLANE ($\delta_b = 0$)

δ_s	Final Pitch (deg)	Final Roll (deg)	Maximum Roll (deg)	Final Depth (ft)
-5	-14	18	50	104
+10	-60	19	36	201
-10	0	18	49	54
+25	-71	10	22	208
-25	31	23	41	-83

From the above tables, it is seen that:

1. A large positive initial stern plane deflection can reduce or even eliminate the roll.
2. A small negative stern plane deflection can be used to control the steady-state pitch.
3. A positive bow deflection of +20° would help reduce undesirable change in depth.

Using the data in Tables 8 and 9, and after much experimentation, the bow and stern plane inputs in Fig. 10a and 10b were determined.

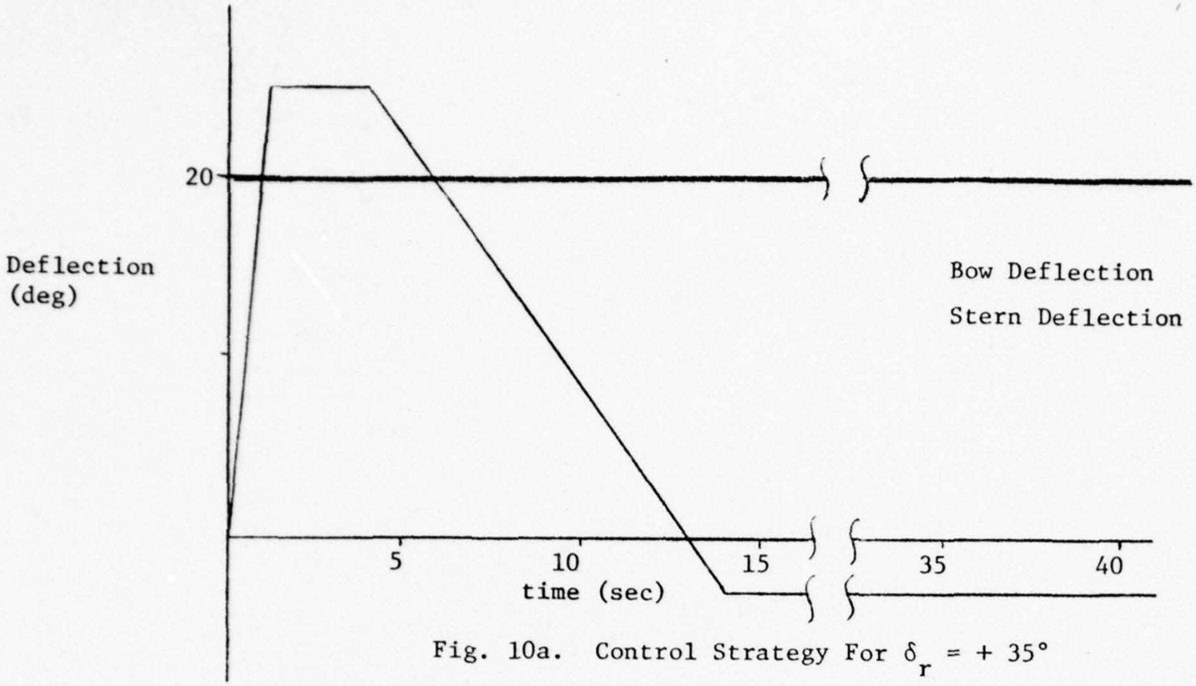


Fig. 10a. Control Strategy For $\delta_r = +35°$

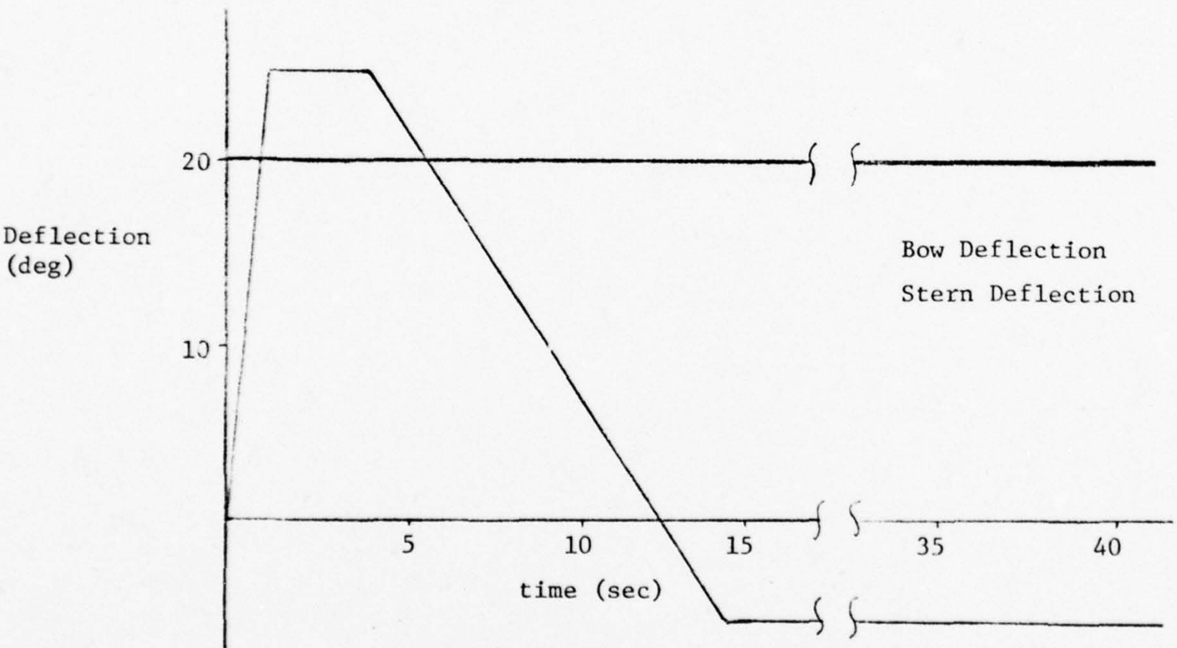


Fig. 10b. Control Strategy For $\delta_r = -35°$

The response to the above manuevers are listed in Tables 10a and 10b. Further, this response is compared to that obtained for the following simple trajectories in Tables 11a and 11b.

TABLE 10a

δ_r = +35° (Our Strategy)
$U_o \equiv$ 8.66 ft/s

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.0	-0.2	-3.3	3.5	-9.4
2	7.0	-2.7	-0.9	5.7	-26.7
3	6.1	-4.7	-1.2	9.9	-44.0
4	5.4	-4.8	-1.2	10.1	-59.8
5	5.0	-4.3	-1.0	4.0	-73.9
6	4.7	-4.5	-0.8	-6.0	-86.9
7	4.5	-5.9	-0.4	-13.2	-98.9
8	4.4	-8.1	0.1	-12.7	-110.4
9	4.3	-9.9	0.9	- 7.2	-121.9
10	4.3	-10.6	1.9	- 4.4	-133.6
11	4.3	10.1	3.1	- 8.6	-145.2
12	4.3	-9.5	4.3	-15.6	-156.6
12.8	4.3	-9.4	5.2	-17.8	-165.6
13	4.3	-9.4	5.5	-17.7	-167.8
14	4.3	-9.6	6.6	-15.7	-179.2
15	4.3	-9.4	7.8	-14.6	-190.7
.	.	.	.	.	.
.	.	.	.	.	.
20	4.3	-6.4	13.1	-16.0	-247.9
.	.	.	.	.	.
.	.	.	.	.	.
40	4.3	-1.1	22.1	-16.0	-476.6

TABLE 10b

$\delta_r = -35°$ (Our Strategy)

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.0	-0.4	-0.3	-0.1	9.4
2	7.0	-3.9	-0.9	0.8	26.5
3	6.1	-7.7	-1.0	-4.6	43.5
4	5.4	-9.0	-0.5	-8.3	59.3
5	5.0	-8.8	0.2	-4.8	73.7
6	4.7	-8.7	1.0	5.7	86.7
7	4.5	-9.8	1.9	16.6	98.8
8	4.4	-12.0	2.9	19.0	110.2
9	4.3	-14.4	4.3	13.1	121.7
10	4.3	-15.8	5.9	7.6	133.5
10.4	4.3	-15.9	6.6	7.3	138.3
11	4.3	-15.6	7.7	9.6	145.4
12	4.3	-14.7	9.6	16.8	157.0
13	4.3	-14.2	11.4	19.8	168.5
14	4.3	-14.0	13.2	17.9	180.0
15	4.3	-13.5	14.9	16.9	191.7
.	.	.	.	.	.
.	.	.	.	.	.
20	4.3	- 8.9	22.6	17.6	249.4
.	.	.	.	.	.
.	.	.	.	.	.
40	4.3	-0.9	34.1	17.9	478.1

Table 11. Comparison of Control Strategies

TABLE a

$\delta_r = +35°$

	Max Pitch, Time	Max Roll, Time	Max Depth, Time	Heading 180° Time
No Control	-23.6, 7.2	-43.7, 3.8	119.0, 40	13.6
$\delta_b=20$, $\delta_s= +25$	-42.6, 40	-13.1, 37.6	100.8, 40	14
$\delta_b=20$, $\delta_s = -25$	33.4, 30.8	-39.6, 3.4	-115.8, 40	13.6
USF	-10.6, 10	-17.8, 12.8	22.1, 40	14

TABLE b

$\delta_r = -35°$

	Max Pitch, Time	Max Roll, Time	Max Depth, Time	Heading 180°Time
No Control	-30.4, 7.4	48.5, 3.8	148.1, 40	13.4
$\delta_b=20$, $\delta_s= +25$	-53.5, 40	18.2, 38.2	128.1, 40	14
$\delta_b=20$, $\delta_s= -25$	31.6, 26.2	43.3, 3.2	-105.3, 40	13.8
USF	-15.9, 10.4	17.9, 14	34.1, 40	14

1. No control system (i.e., $\delta_s = 0$, $\delta_b = 0$)
2. $\delta_s = 25°$, $\delta_b = 20°$ steps
3. $\delta_s = -25°$, $\delta_b = 20°$ steps

All of these simple strategies are inferior or totally unacceptable compared to ours.

The roll response of our control strategy is compared to the roll responses of the above strategies in Fig.11. (Note: Although the roll for the simple strategy 2 may look acceptable, the corresponding depth response is disasterously bad -- the vehicle dives continually.)

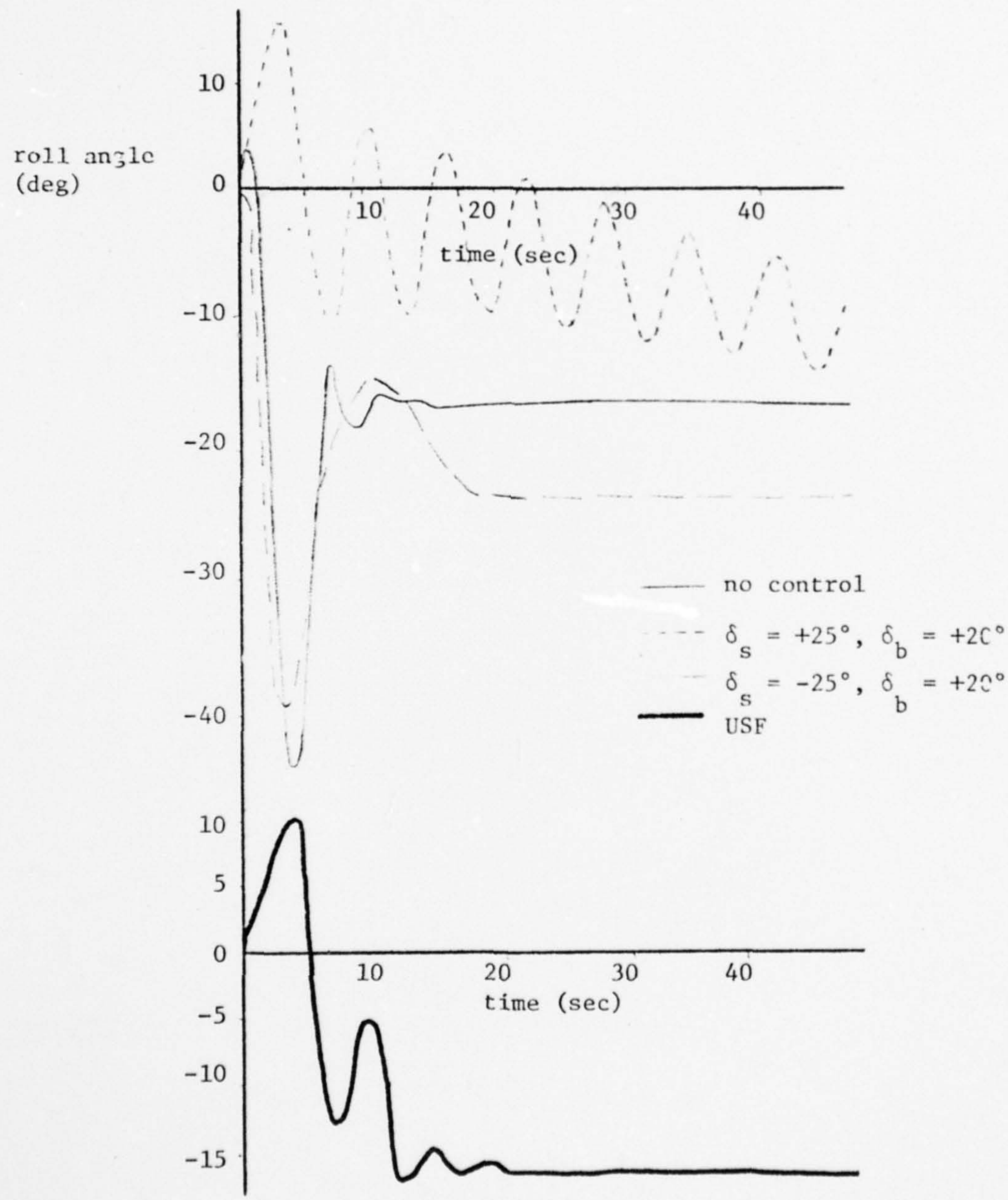


Fig.11. Comparison of Roll Responses

δ_r = 20°: Open-Loop

To test the versatility of our strategy, (large positive stern plane deflection of short duration followed by a small negative stern plane deflection together with a constant positive bow plane deflection for the duration of the run) we next examine the case of a $\pm 20°$ hard rudder. The stern and bow plane inputs devised for this case are shown in Fig.12.

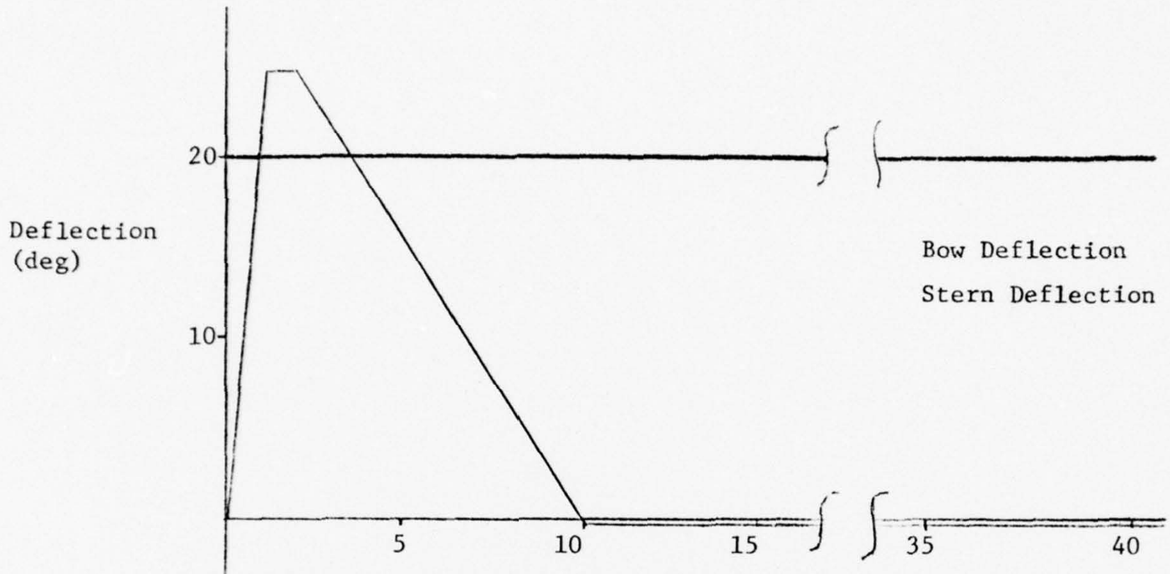


Fig. 12a. Control Strategy For δ_r = +20°

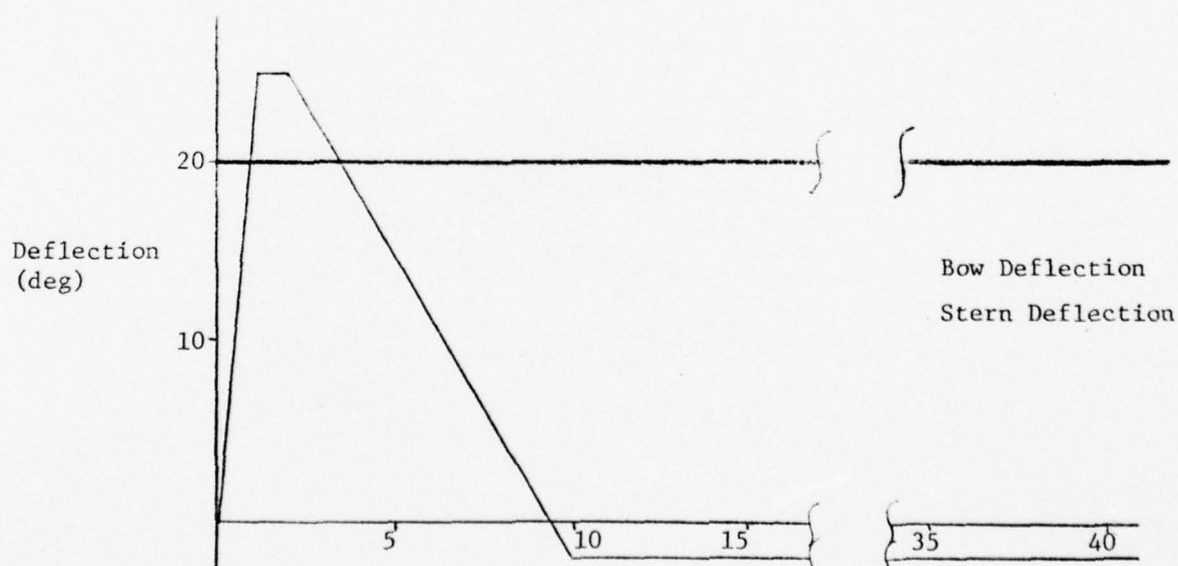


Fig. 12b. Control Strategy For δ_r = -20°

The responses to these trajectories are listed in Tables 12a and 12b.

TABLE 12a

$\delta_r = +20°$ (Our Strategy)

Time (sec)	Speed (ft/sec)	Pitch (deg)	Depth (ft)	Roll (deg)	Heading (deg)
0	8.7	0.0	0.0	0.0	0.0
1	8.3	-0.4	-0.3	2.5	-5.7
2	7.8	-4.2	-0.9	1.6	-17.1
3	7.1	-9.1	-1.1	0.5	-29.9
4	6.5	-12.5	-0.5	1.7	-42.6
5	6.1	-14.0	0.8	2.7	-55.0
5.4	6.0	-14.1	1.39	2.17	-59.9
6	5.8	-14.0	2.4	-0.4	-66.9
7	5.7	-13.5	4.1	-8.0	-78.2
8	5.5	-13.2	5.8	-16.0	-88.9
9	5.5	-13.4	7.6	-18.6	-99.2
10	5.4	-13.3	9.4	-16.7	109.5
11	5.4	-12.5	11.3	-14.9	-119.8
12	5.4	-11.0	13.0	-14.7	-129.9
13	5.4	-9.3	14.6	-14.9	-139.8
14	5.4	-7.7	16.0	-14.8	-149.5
15	5.4	-6.3	17.1	-14.8	-159.3
16	5.4	-4.9	18.0	-14.8	-169.0
17	5.4	-3.7	18.6	-14.9	-178.8
17.2	5.4	-3.5	18.7	-14.9	-180.7
.	.	.	.	.	.
.	.	.	.	.	.
20.0	5.4	-0.6	19.4	-15.2	-206.2
20.2	5.4	-0.4	19.4	-15.2	-208.2
.	.	.	.	.	.
.	.	.	.	.	.
40.0	5.4	10.6	-2.6	-15.7	-408.4

TABLE 12b

δ_r = -20 (Our Strategy)

Time (sec)	Speed (ft/sec)	Pitch (deg)	Depth (ft)	Roll (deg)	Heading (deg)
0.0	8.7	0.0	0.0	0.0	0.0
1.0	8.3	-0.5	-0.3	0.9	5.6
2.0	7.8	-5.0	-1.0	4.3	16.8
3.0	7.1	-11.1	-0.9	4.9	29.0
4.0	6.5	-15.6	0.1	1.9	41.5
5.0	6.1	-17.6	1.8	-0.5	54.1
5.6	6.0	-17.8	3.1	0.5	61.4
6.0	5.9	-17.8	4.0	2.6	66.2
7.0	5.7	-17.3	6.3	11.7	77.6
8.0	5.5	-17.2	8.6	20.9	88.4
8.8	5.5	-17.5	10.5	23.1	96.8
9.0	5.5	-17.6	11.0	22.9	98.9
10.0	5.4	-17.8	13.0	20.5	107.3
11.0	5.4	-16.9	16.1	17.5	120.0
12.0	5.4	-15.2	18.6	17.0	130.3
13.0	5.4	-13.3	20.9	16.8	140.3
14.0	5.4	-11.3	22.9	16.6	150.2
15.0	5.4	- 9.5	24.6	16.6	159.9
16.0	5.4	- 7.8	26.0	16.8	169.7
17.0	5.4	- 6.3	27.2	17.0	179.4
.	.	.	.	.	.
.	.	.	.	.	.
20.0	5.4	- 2.5	29.2	17.6	208.8
.	.	.	.	.	.
.	.	.	.	.	.
40.0	5.4	-10.1	11.1	18.7	408.6

As observed in the preceding discussion, the inclusion of a large positive stern plane deflection at the beginning of a hard rudder maneuver, effectively reduces or eliminates the snap roll, (for +35° rudder, snap roll was reduced from -43.7° to -17.8° when compared to uncoordinated hard rudder). After the (initial) large positive stern plane deflection, and its gradual relaxation to zero, a small negative value is required for the duration of the maneuver to control and maintain depth (for the +35° rudder case, the depth change, 119.0 ft with no coordinated control, was reduced to 22.1 ft. by our strategy).

Also consider the case of +20° hard rudder. Our control strategy for this case results in a max roll of -18.6° and a maximum depth deviation of -8.5 feet. The corresponding values for the uncontrolled case, i.e. when the +20° is not accompanied by stern and bow deflections, are -32° and 67 ft. This improvement is quite significant. It may also be noted that a 180° turn is achieved for the two cases ($+35°\delta_r$, $+20°\delta_r$) in 14 second and 17.2 second, respectively.

Closed Loop

After the completion of phase 1, with control strategies determined for ±35° rudder manuever, the actuation of bow and stern plane inputs is examined in a feedback configuration. This incorporation of the control strategy into a closed loop in the subroutine AUTO constitutes phase two of roll control development.

The proposed feedback system consists of two subsystems:

Yaw-rate Actuated Subsystem: This consists of two positive relays, both actuated by the vehicle yaw-rate. They generate (i) a component δ_{s_r} for the stern plane, and (ii) a component δ_{b_r} for the bow plane. REL_s furnishes the short duration +25° stern plane deflection at the beginning of the manuever, and REL_b a constant +20° bow plane deflection for the entire duration of the rapid turn manuever.

Linear Subsystem: This consists of the longitudinal control system previously existing in the NCSL trajectory program augmented by the output of a leaky integrator, excited by depth error, to the stern plane (see Fig. 13). The intent of the augmentation is to control vehicle depth during rapid-turn as well as to fine-tune it (back to the ordered value) in the steady-state.

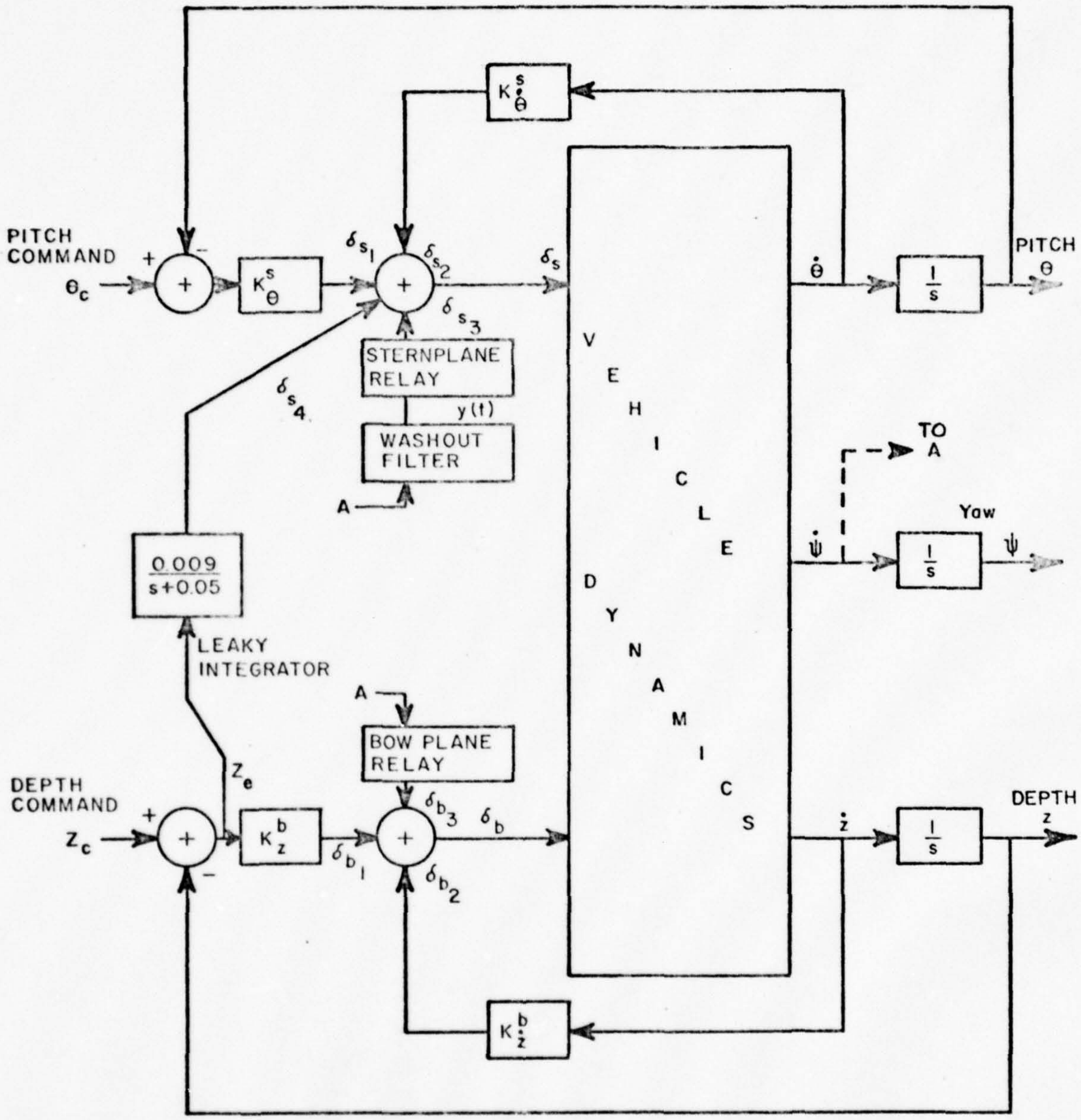
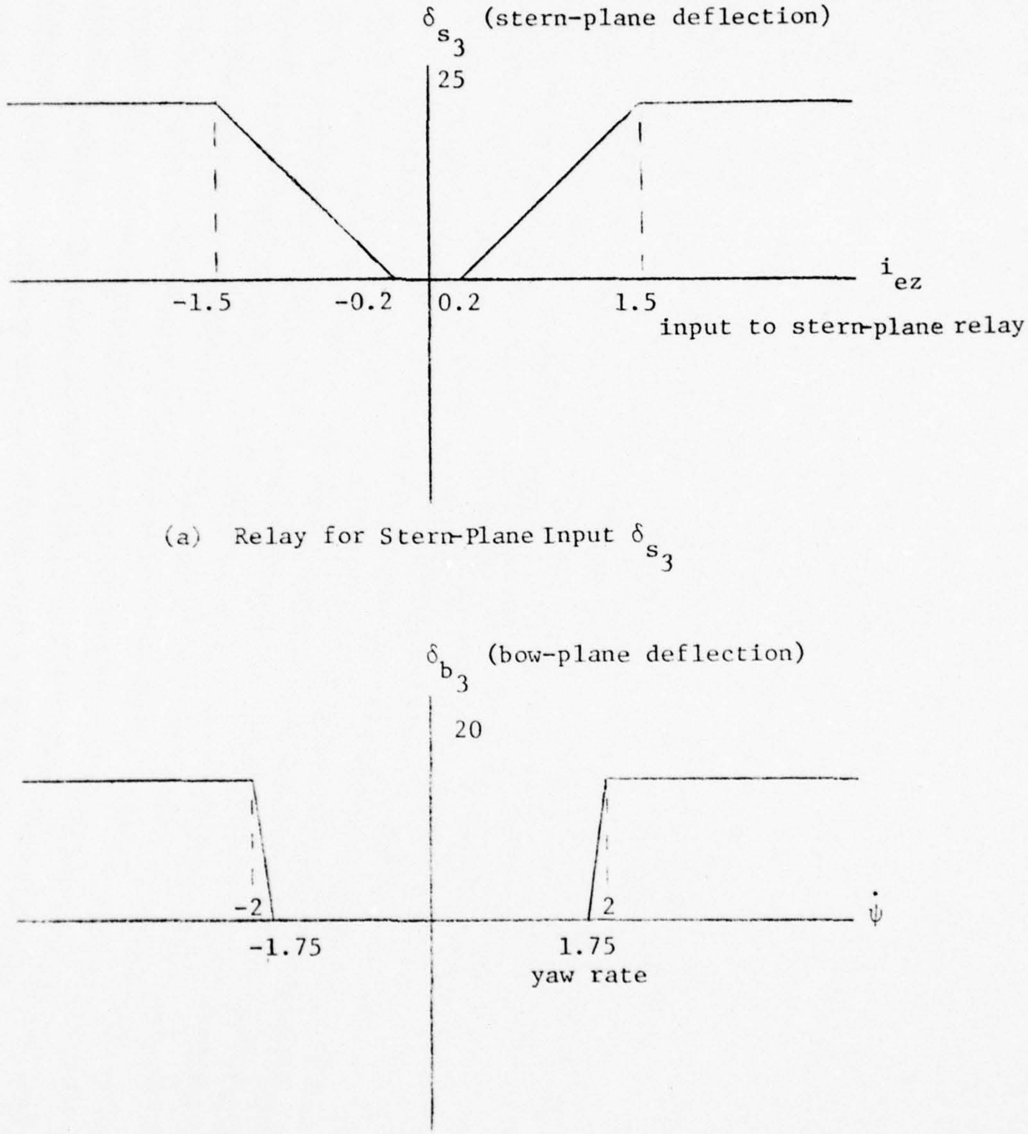


Fig. 13. Turn Control System by Augmenting the LLCS (Linear Control System) by Stern and Bow Plane Relays and a Leaky Integrator.

$\dot{\psi}$ Actuated Subsystem

The heading rate is the sampled quantity because the roll is intimately related with large heading rate. We will use this signal to actuate the stern and bow planes in order to control the roll. In particular, the components δ_{s_r} and δ_{b_r} are produced by positive relays shown in Fig.14.



(a) Relay for Stern-Plane Input δ_{s_3}

(b) Relay for Bow Plane Input δ_{b_3}

Fig.14. Positive relays for generating component 3 to stern and bow-plane inputs.

The input to the bow plane relay is the heading rate itself because a large positive bow deflection is required throughout the duration of the rapid turn. The input to the stern plane relay, however, is a signal produced by the washout filter (Fig. 15) which produces a transient pulse just long enough to actuate the relay for a few seconds at the beginning of the turning maneuver. It should also be noted that the relay is enabled for a duration dependent upon the severity of the turning rate. That is, the higher the turning rate, the longer the deviation for which the relay yields a +25° stern plane signal.

The design of the filter is discussed briefly. For +35° rudder input the heading rate is shown in Fig. 16.

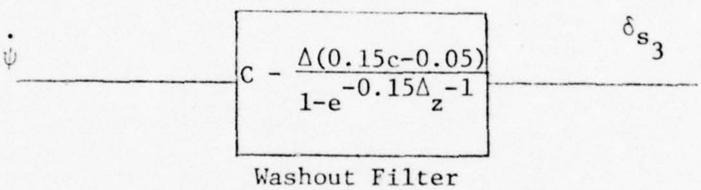


Fig. 15. Washout Filter

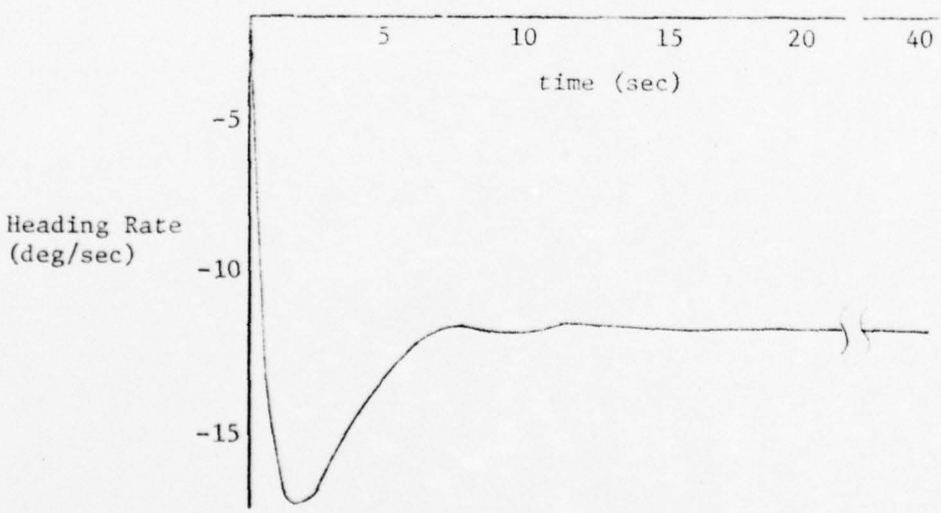


Fig. 16. $\dot{\psi}$ Response

The open loop snap roll control strategy had shown that the stern plane must stay at +25° from approximately 2 sec to about 5 seconds. We therefore demand the following approximate behavior from the filter to a step input (consider the heading rate to be like a delayed step input, for the moment - see Fig.14).

Response specifications for a first order filter to a unit step

Peak at 2 sec

Decay to e^{-1} = 0.37 fraction at 7 sec

Time constant = 6 sec

Pole = 0.15

Steady State Response = 0.33 fraction

The transfer function must therefore be of the form:

$$H(s) = \frac{cs + 0.05}{s + 0.15}$$

$$= \frac{cs}{s + 0.15} + \frac{1}{3}$$

where we must determine a suitable value for c. Consider the delayed step response

$$H(s)\ \frac{e^{-s}}{s} = \left(\frac{c}{s+0.15} + \frac{1}{3s}\right) e^{-s}$$

or in the time domain would be:

$$y = \left[ce^{-0.15(t-1)} + \frac{1}{3}\right] u(t-1)$$

After the above equation is deemed to deliver the correct activating signal to the stern plane relay, the equation was encoded into z-domain, and incorporated in a difference equation. This entire operation is put in the program as a filter, and is called the 'washout filter' [1].

$$y = \left\{c - \frac{\Delta(0.15c - 0.05)}{1 - e^{-0.15\Delta}z^{-1}}\right\} \dot{\psi}$$

AUX(k+1) = Q *AUX(k)+ P * PSIDOT

Y(k+1) = -AUX(k) + C * PSIDOT

where *

$Q = e^{-0.15\Delta}$ C = 15

$P = \Delta\ (0.15c - 0.05)$

* NOTE: Δ = ISCCN*DT because the subroutine AUTC is called only once every ISCON integration steps.

Linear Subsystem

A leaky integrator is incorporated into the control system to include an accumulative depth error correction to the stern plane. Specifications for the integrator are shown in Fig. 17.

The difference equation introduced in subroutine AUTO [4] is given below [6].

$$DS4(k+1) = Q * S4(k) + P * ZERR(k+1)$$

where

$$Q = e^{-0.05\Delta} \qquad P = 0.009\Delta$$

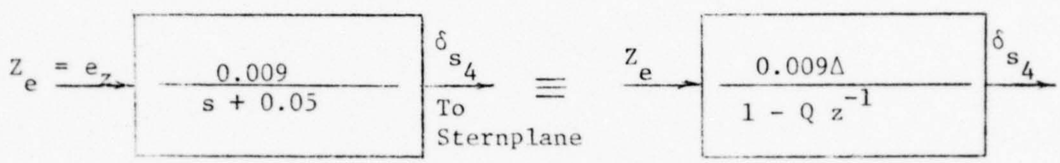


Fig. 17. Leaky Integrator: From Z_e to Sternplane

The bow manuever is generated by the positive bow plane relay activated by the heading rate.

The automatic control (summation of corrective manuevers from the relay, integrator, and linear control sytem initially present in subroutine AUTO) generates the bow and stern plane deflection shown in Fig. 18 and 19 for +35° and +20°. The ± 20° hard rudder runs were made to test the versatility of the control system. The roll responses for +35° and +20° hard rudder with the automatic control activated are compared to those obtained (a) without any stern plane or low plane control and (b) with our open-loop control strategy. These are shown in Fig. 20 and 21.

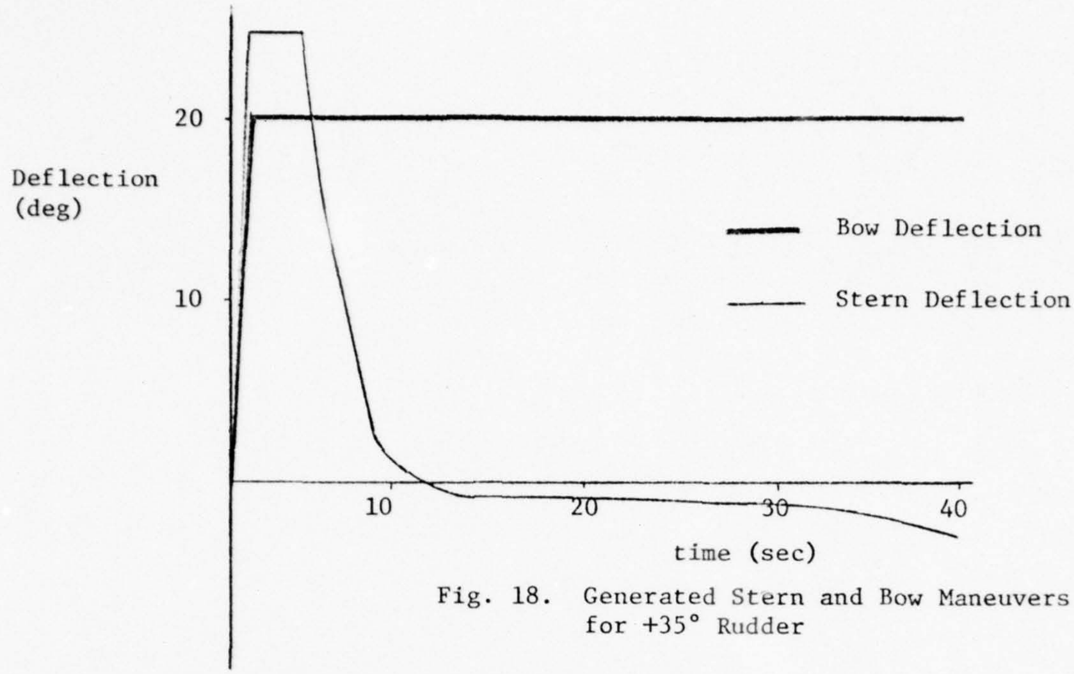


Fig. 18. Generated Stern and Bow Maneuvers for +35° Rudder

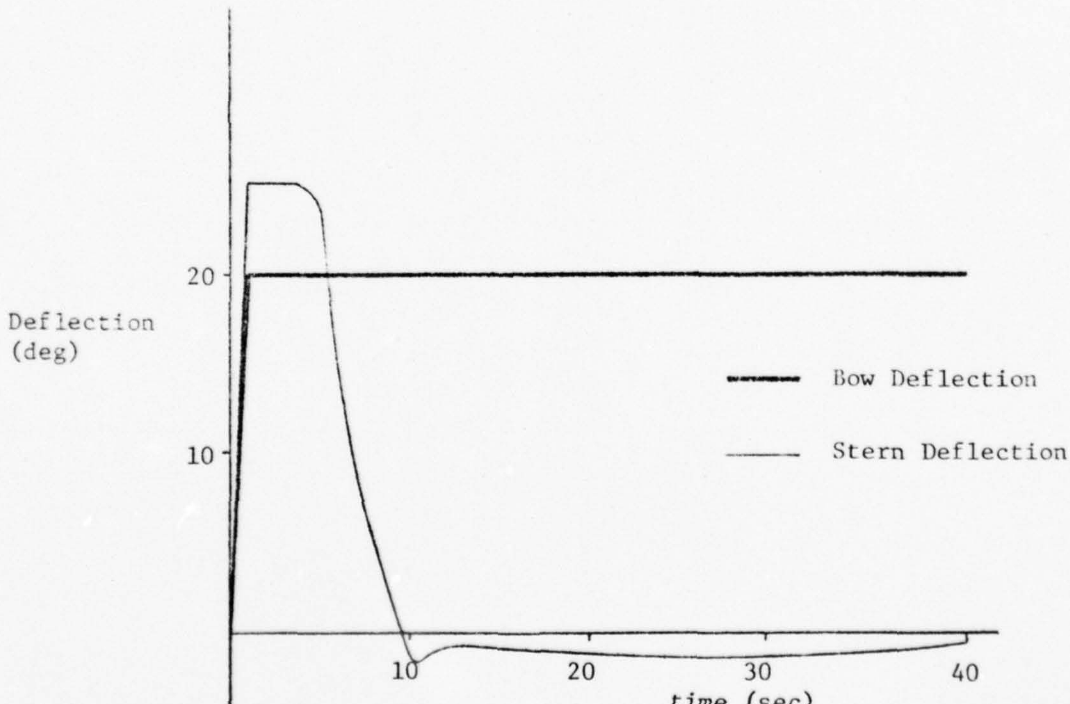


Fig. 19. Generated Stern and Bow Maneuvers for +20° Rudder

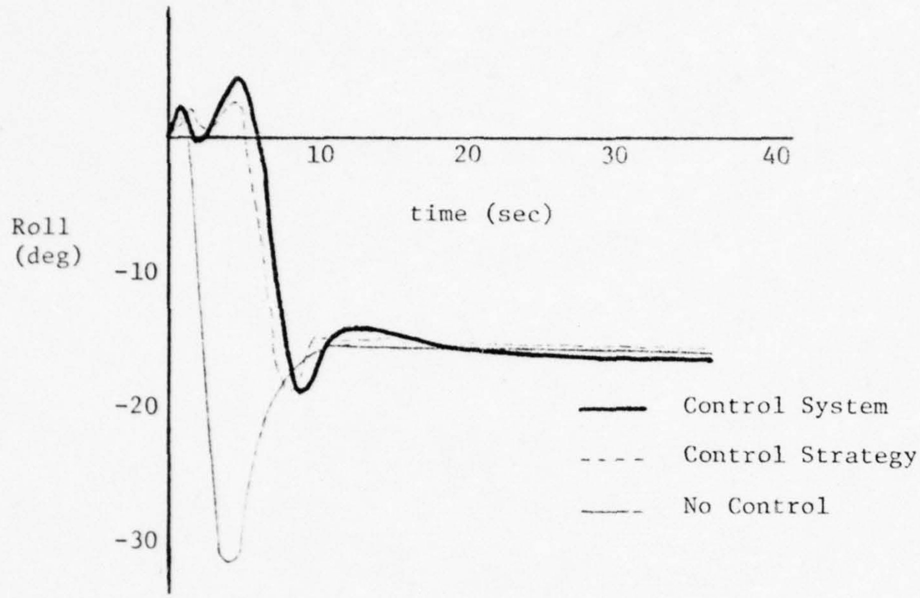


Fig. 20. Roll Responses for +20° Rudder

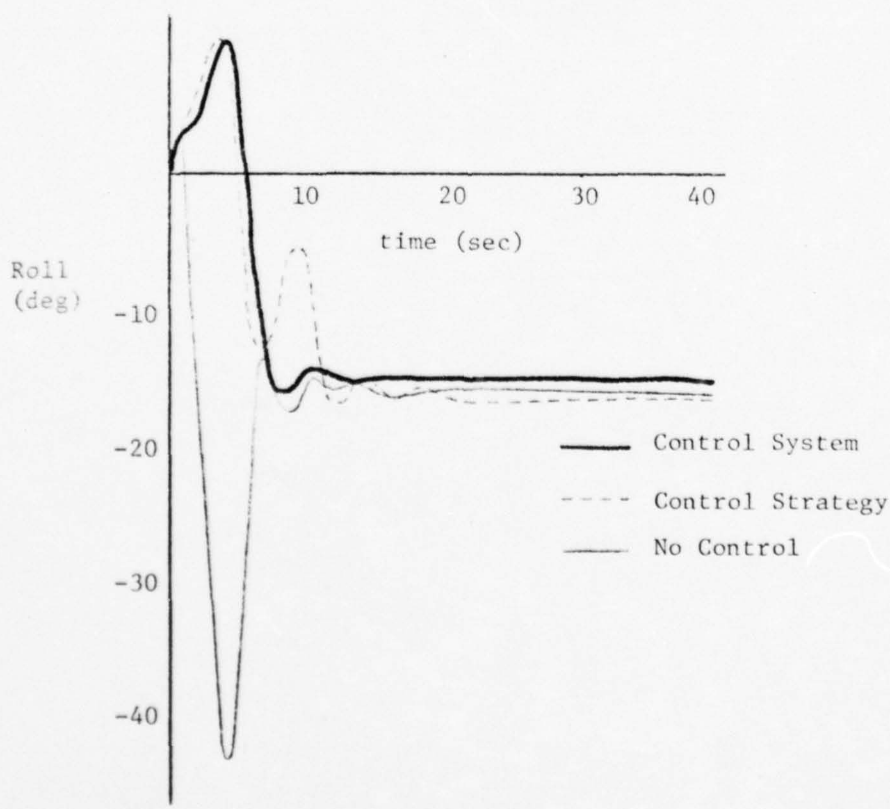


Fig. 21. Roll Responses for +35° Rudder

The responses of our control system to $\pm35°$ rudder deflection and $\pm20°$ rudder deflection are listed in Table 13a and 13b and Table 14a and 14b respectively.

TABLE 13a

$\delta_r = +35°$ (Automatic Control)

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.1	-0.4	-0.3	3.6	-9.5
2	7.1	-2.2	-0.8	3.7	-26.8
3	6.1	-4.5	-1.1	7.5	-44.2
4	5.4	-5.2	-1.1	9.4	-60.0
5	5.0	-4.9	-0.8	5.2	-74.3
6	4.7	-5.0	-0.5	-3.4	-87.4
7	4.5	-5.8	-0.1	-11.8	-99.5
8	4.4	-6.9	0.4	-16.4	-111.1
8.4	4.4	-7.3	0.7	-16.8	-115.7
9	4.3	-7.9	1.2	-16.2	-122.6
10	4.3	-8.5	2.1	-14.3	-134.1
10.4	4.3	-8.5	2.5	-13.9	-138.8
11	4.3	-8.4	3.1	-14.0	-145.7
12	4.3	-8.0	4.1	-15.3	-157.1
13	4.3	-7.5	5.1	-16.1	-168.5
14	4.3	-7.3	6.1	-15.7	-179.9
15	4.3	-7.1	7.0	-15.3	-191.3
.	.	.	.	.	.
.	.	.	.	.	.
20	4.3	-6.2	11.3	-15.6	-248.5
.	.	.	.	.	.
.	.	.	.	.	.
40	4.3	-3.2	23.6	-15.9	-477.4

TABLE 13b

$\delta_r = -35°$ (Automatic Control)

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.0	-0.4	-0.3	-0.2	9.4
2	7.1	-3.3	-0.9	3.2	26.5
3	6.1	-7.4	-1.1	-1.6	43.5
4	5.4	-9.5	-0.6	-7.5	59.3
5	5.0	-9.5	-0.2	-6.5	73.7
6	4.7	-9.3	1.1	2.3	86.9
7	4.5	-9.7	2.1	14.0	99.2
8	4.4	-10.8	3.1	21.2	110.7
8.4	4.4	-11.4	3.6	21.7	115.3
9	4.3	-12.3	4.4	20.2	122.2
10	4.3	-13.3	5.8	16.1	133.8
10.6	4.3	-13.5	6.7	14.8	140.8
11	4.3	-13.5	7.4	14.9	145.5
12	4.3	-13.0	9.1	16.7	157.2
13	4.3	-12.4	10.7	17.8	168.7
14	4.3	-12.0	12.3	17.4	180.2
15	4.3	-11.7	13.8	17.0	189.4
.	.	.	.	.	.
.	.	.	.	.	.
20	4.3	-10.5	21.0	17.4	249.4
.	.	.	.	.	.
.	.	.	.	.	.
40	4.3	-7.0	43.2	17.5	479.7

TABLE 14a

δ_r = +20° (Automatic Control)

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.5	-0.5	0	2.2	-5.7
2	7.9	-3.3	-0.2	-0.7	-17.5
3	7.2	-8.2	-0.2	-0.3	-30.6
4	6.6	-12.2	0.5	2.2	-43.7
5	6.1	-14.6	1.8	4.3	-56.5
6	5.8	-15.9	3.5	3.7	-68.7
6.8	5.6	-16.2	5.0	1.1	-78.0
7	5.6	-16.2	5.4	0	-80.3
8	5.4	-15.9	7.4	-7.3	-91.2
9	5.4	-15.3	9.5	-15.5	-101.7
10	5.3	-14.7	11.6	-18.8	-111.8
11	5.3	-13.9	13.6	-17.0	-122.0
12	5.3	-12.7	15.6	-14.8	-132.0
13	5.3	-10.9	17.4	-14.1	-141.9
14	5.3	-8.9	19.0	-14.2	-151.6
15	5.4	-7.1	20.4	-14.3	-161.2
16	5.4	-5.4	21.4	-14.5	-170.8
17	5.4	-3.9	22.2	-14.7	-180.4
.	.	.	.	.	.
.	.	.	.	.	.
20	5.4	-0.1	23.0	-15.3	-209.7
.	.	.	.	.	.
.	.	.	.	.	.
40	5.4	13.2	-4.5	-16.2	-410.9

TABLE 14b

δ_r = -20° (Automatic Control)

TIME (sec)	SPEED (ft/sec)	PITCH (deg)	DEPTH (ft)	ROLL (deg)	HEADING (deg)
0	8.7	0	0	0	0
1	8.5	-0.6	0	1.3	5.7
2	7.9	-4.1	-0.2	7.3	17.2
3	7.2	-10.5	0	-6.5	29.6
4	6.1	-15.8	1.1	-1.8	42.4
5	6.1	-18.9	3.0	-2.2	55.2
6	5.8	-20.5	5.3	-2.4	67.8
7	5.6	-21.1	7.9	1.5	79.7
7.4	5.5	-21.2	8.9	4.3	84.2
8	5.4	-21.1	10.6	9.5	90.9
9	5.3	-20.8	13.5	18.4	101.6
10	5.3	-20.6	16.3	21.8	112.1
10.6	5.3	-20.4	18.1	20.9	118.3
11	5.3	-20.1	19.3	19.7	122.5
12	5.3	-19.1	22.2	17.1	132.8
13	5.3	-17.3	25.0	16.2	143.0
14	5.3	-15.3	27.5	16.1	152.9
15	5.4	-13.3	29.9	16.1	162.7
16	5.4	-11.4	31.9	16.3	172.4
16.8	5.4	-10.1	32.9	16.5	180.2
.	.	.	.	.	.
.	.	.	.	.	.
20	5.4	-5.6	37.4	17.3	211.6
.	.	.	.	.	.
.	.	.	.	.	.
24.8	5.4	-0.1	39.2	17.9	258.7
.	.	.	.	.	.
.	.	.	.	.	.
40	5.4	10.3	23.4	18.9	410.7

It must be emphasized that the implementation of the new strategy poses some uniquely difficult problems. To name a few, a) it cannot be implemented via a linear controller, b) it must come into play selectively, i.e., only when relatively hard rudder is applied, and c) the duration of the activation of the positive relays (see Fig.12) has to be controlled in correspondence with the amplitude of the hard rudder. As can be observed from Tables 14a and 13a (showing maximum rolls of -16.7^{o} and -18.8^{o} for -35^{o} and -20^{o} step rudders, respectively), our automatic control system needs some fine tuning. From Fig. 20 and 21 it is seen that the stern plane component δ_{s_3} for $+35^{o}$ and $+20^{o}$ rudder steps are very similar; they should not be, and the duration of positive stern plane for the $+20^{o}$ rudder step should have been shorter that it is. Further work must be done to redesign the washout filter of Fig.15 so as to better adjust the duration of positive maxima of the stern plane component δ_{s_3}. However, it is felt that the basic configuration proposed here is adequate for achieving the new turn control strategy in a feedback mode.

REFERENCES

[1] J. H. Blakelock, Automatic control of aircraft and missles, John Wiley and Sons, Inc., 1965.

[2] D. E. Humpreys, "Development of the equations of motion and transfer functions for underwater vehicles", Naval Coastal Systems Laboratory Technical Report NCSL 287-761, July, 1976.

[3] M. Abkowitz, Stability and motion control of ocean vehicles, MIT Press, Cambridge, Massachusetts, August, 1972.

[4] Users guide for the NCSC/TRAJOBJ computer program, Hydromechanics Division, Naval Coastal Systems Center, September, 1978.

[5] J. E. Gibson, Nonlinear automatic control, McGraw-Hill Book Co., 1963.

APPENDIX A

VEHICLE PARAMETERS

(Data Cards Inputted to
NCSC Trajectory Program)

```
04440 --- U S F RPV --- REMOTELY PILOTED VEHICLE --- QF II EOMS ---
04450               16
04460                1              2              3              4              5              6
04470               97            100             98             31             30             33
04480               23             19             26             24
04490                4              4              4              4              4              4
04500                4              4              4              4              4              4
04510                4              4              4              4              4              4
04520 -0.20900E-030.               0.             0.             0.             0.
04530 -0.32400E-02-0.26670E-02-0.15700E-02-0.17100E-03+0.51000E-040.
04540 +0.10880E-01+0.37000E-02-0.10110E-010.
04550               19
04560                1              2              3              4              5              6
04570              108            120             13             44             29             32
04580               17              7              9             25             48             57
04590               58
04600                4              4              4              4              4              4
04610                4              4              4              4              4              4
04620                4              4              4              4              4              4
04630                4              4              4              4              4              4
04640 0.            -0.10880E-010.            -0.51000E-040.               0.
04650 +0.75920E-02+0.13450E-02-0.72200E-030.            +0.17100E-030.
04660 +0.30010E-020.            -0.22000E-01+0.10110E-01-0.16150E-01-0.64307E+00
04670 -0.12077E+00
04680               17
04690                1              2              3              4              5              6
04700               47            105            106            121             28             15
04710                7             21             11             59             60
04720                4              4              4              4              4              4
04730                4              4              4              4              4              4
04740                4              4              4              4              4              4
04750 0.             0.            -0.10110E-010.            -0.17100E-030.
04760 -0.78300E-03-0.43400E-02-0.54860E-02-0.97200E-030.               -0.54610E-02
04770 -0.17700E-03-0.10880E-01-0.12960E-01-0.10000E+01+0.12077E+00
04780               18
04790                1              2              3              4              5              6
04800              108             13             44             29             32             17
04810                7              9             65             25             90             58
04820                4              4              4              4              4              4
04830                4              4              4              4              4              4
04840                4              4              4              4              4              4
04850 0.            -0.51000E-040.            -0.33000E-050.               -0.18000E-05
04860 +0.52000E-04-0.58000E-040.             0.            +0.15000E-04-0.28100E-04
04870 +0.67963E-05-0.60948E-03+0.16348E-03+0.51000E-04+0.22076E-03-0.28215E-03
04880               18
04890                1              2              3              4              5              6
04900               47            105            106            121             15             30
04910                7             11             49             52             63             64
04920                4              4              4              4              4              4
04930                4              4              4              4              4              4
04940                4              4              4              4              4              4
04950 0.             0.            -0.16800E-030.            -0.49900E-030.
04960 -0.41300E-04+0.82300E-03-0.25210E-02-0.52700E-03-0.32370E-02+0.48070E-03
04970 -0.39500E-04+0.44420E-02-0.60292E-02-0.51622E-03+0.10000E+01-0.12077E+00
04980               17
04990                1              2              3              4              5              6
```

```
            108         120         13          29          17           7
              9          25         48          61          62
              4           4          4           4           4           4
              4           4          4           4           4           4
              4           4          4           4           4           4
0.          0.          0.          -0.18000E-050.          -0.48400E-03
-0.36100E-02-0.75460E-03-0.61000E-04-0.49600E-03-0.28940E-020.
-0.73080E-02-0.17100E-03+0.87682E-02-0.64307E+00-0.12077E+00
+0.23500E+02
0.          +0.15833E+00+0.45166E+00+0.81333E+00+0.12200E+01+0.15700E+01
+0.18550E+01+0.22983E+01+0.24983E+01+0.26650E+01+0.27316E+01+0.27500E+01
+0.27500E+01+0.26583E+01+0.25183E+01+0.24200E+01+0.22266E+01+0.189333+01
+0.13666E+01+0.10116E+01+0.77833E+00+0.44333E+000.
0.          +0.15833E+00+0.45166E+00+0.81333E+00+0.12200E+01+0.15700E+01
+0.18550E+01+0.22983E+01+0.24983E+01+0.26650E+01+0.27316E+01+0.27500E+01
+0.27500E+01+0.26583E+01+0.25183E+01+0.24200E+01+0.22266E+01+0.189333+01
+0.13666E+01+0.10116E+01+0.77833E+00+0.44333E+000.
-0.16493E+02-0.16222E+02-0.15722E+02-0.15056E+02-0.14222E+02-0.13389E+02
-0.12555E+02-0.10889E+02-0.92225E+01-0.75558E+01-0.60975E+01-0.49725E+01
+0.85223E+01+0.10092E+02+0.10758E+02+0.11092E+02+0.11592E+02+0.12258E+02
+0.12925E+02+0.13258E+02+0.13425E+02+0.13592E+02+0.13673E+02
+0.63676E+00+0.64938E+00+0.42280E+01-0.20017E+01+0.48508E+01-0.16514E+02
+0.13200E+01-0.38500E-01+0.83117E+010.          0.          -0.10000E+01
+0.29708E-01-0.14298E+020.          0.          +0.70270E-03-0.19979E-01
+0.54509E+01+0.21255E+00+0.20243E+03+0.15132E-04-0.98800E-02-0.10000E-02
-0.95000E-03+0.19500E-02-0.10000E-020.          +0.10000E-02-0.10000E-02
0.          -0.40000E-03-0.10000E-03+0.25000E-03-0.12500E-02+0.10000E+01
0.          -0.10000E+01-0.14298E+02+0.83333E-01+0.48258E+01-0.21942E+01
-0.14575E+02
+0.90683E+040.          0.          0.          +0.90683E+040.
0.          -0.83333E-01+0.24482E+03+0.15091E+05+0.15091E+050.
0.          0.          +0.30167E+02+0.13673E+02
----U S F RPV ----RUDDER STEP 1 DEG --- SPEED IS 1.44
STOPTM=040.0 OUTT=.20  DT=0.100  ISCON=  1 IPLOT= 0 INTOPT= 0 IPUNCH= 00
IFIXSP = 1 SZCC    = 0.0090
ISTOUT =01
INITIALS       8.66 00000 00000  0000 00000 C0000 00000 00000 00000
  STATE        0.000  1000.
ICON IREC      02 0 0 0 0 0 0-1-1-1-1-1-1
DBBB             00.0 24.23 020.0 1000. +05.0 000.0 1.000 25.00 .1605 0.00
DB             500.0 3.000
 DRRR            +35.0 24.25 35.00 +26.0 35.00 +20.0 0005. 0001. .1605 0.00
DR             500.0 2.000
DSSS             000.0 24.25 25.00 000.0 -02.00-7.880 5.00 25.00 .1605 0.000
DS             500.0 10.00
PROP           492.4 75.00 0.000 8.666 246.2 492.4 11.11 0.000 0.000 0.000
PROP           500.0 0.000
OFF            0.000 0.000 0.000 0.000 0.000 0.000 .0023 .0058 .1605 0.000
OFF            500.0 0.000
BLFGG            0.0 000.0 1.0  -25.  07.0  -25.0 17.0   20.0 200.0 20.0
BLFG
BLFG
BLFG
 RLFGG           0.0 0.000 1.2  -10.  004.  -10.  007.  -35.  500.0 -35.
  RLFG           500. -35.0
RLFG
```

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```
RLFG
SLFGG           0.0 000.0 1.2  +25.  02.0  +25.0 010.  -2.0  500.0 -2.0
 SLFG
SLFG
SLFG
PLFG
PLFG
PLFG
PLFG
NT           02
BRI          .2867 .1824 0.000 0.000 0.000 0.000
XT           10.25 -12.580.000 0.000 0.000 0.000
ALFA         -0.19 -0.13 0.000 0.000 0.000 0.000
TBLST        0.000 0.000 0.000 0.000 0.000 0.000
TBLSP        500.0 500.0 0.000 0.000 0.000 0.000
VT           11.38 5.493 0.000 0.000 0.000 0.000
EPA EDS      -45.0 25.00
DPSID        0.500
PROPT U(5)   0.000 0.000
SLFG 1          0.0 -25.0 07.  -25.  13.5  -03.5 200.  -03.5
SLFG
SLFG
SLFG
BLFG            0.0 -20.0 05.  -20.  10.0  +20.0 200.  +20.0
BLFG
BLFG
BLFG
SLFG 2          0.0 000.0 1.2  -25.  07.0  -25.   14.0 02.5  200.0 02.5
SLFG
SLFG
SLFG
BLFG 2          0.0 000.0 1.0  -20.  010.  -20.   15.00  20.00 200.00  20
BLFG
BLFG
BLFG
//


135   CONTINUE
```

APPENDIX B

```
//ZU0174NE JOB (,,,R033,60,30,5),'KAUTZ',CLASS=D,NOTIFY=ZU0174
//STEPZ EXEC FTG1CLG,LIB5='USF.OU.P0549.$DOBECK.LINKLIB'
//FORT.SYSIN DD *
C
C
C
C
C
C
C
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 FIR,SEC,THR,FOR
C
      DIMENSION TEA(6),NSIL(15),R(501,6)
      DIMENSION FOR(501,2)
      DIMENSION FIR(501,2),SEC(501),THR(501)
      COMMON /QFSAV/PDD(1556),IPDD,NOWS
      COMMON /PRIN2/OUTT,SZERR,ZPOLE,SZC,DRC,SPHERR,PHPOLE,DUM1,DUM2
      COMMON /PRIN4/CC,SAMRAT,PSIPOL,DTT,SIMPSI
      COMMON /PRIN3/ISTOUT
C
C
      COMMON X(30),XD(30),TITLE(12),
     A DB(12),DS(12),DR(12),PROP(12),OFF(12),CLIP(10),
     B BLFG(2,20),SLFG(2,20),RLFG(2,20),PLFG(2,20),
     C BRI(6),ALFA(6),XT(6),TBLST(6),TBLSP(6),VT(6),VOL(6),
     D EPA,EDS,DPSID,DT,TIME,STOPTM,PAD(11),
     E NT,ICON(7),IREC(6),I1,INVOPT,ICHK,IPAD(5),NST
C
      COMMON/PRIN/PRI(501,12),PRINT(20),TLAB(12),JPLOT,IPLOT,IRNUM
      COMMON /STO/NSTOP
      COMMON /ILL/IFIXSP
      CALL COEFIO(IDUM,UPRPM)
      IRNUM=0
   10 READ(5,20,END=110)TITLE
   20 FORMAT(12A6)
      WRITE(6,30)TITLE
   30 FORMAT(1H1,5X,12A6)
      READ(5,40)STOPTM,OUTT,DT,ISCON,IPLOT,INTOPT,IPUNCH
      NSTOP=STOPTM
      READ(5,41)IFIXSP,SZC
      READ(5,526)ISTOUT
526   FORMAT(8X,I2)
41    FORMAT(9X,I2,9X,F10.5)
40    FORMAT(7X,F6.2,5X,F6.2,3X,F6.2,7X,I3,7X,I2,8X,I2,8X,I2)
      WRITE(6,50)STOPTM,OUTT,DT,ISCON,IPLOT,INTOPT,IPUNCH
      WRITE(6,51)IFIXSP,SZC
      WRITE(6,527)ISTOUT
527   FORMAT(/,3X,'STANDARD OUTPUT OPTION =',I2,3X,'0=STAN. OUT.',/)
51    FORMAT(//,6X,'IFIXSP =',I3,3X,'SZERR CONSTANT =',E10.2)
   50 FORMAT(//6X,'STOP TIME =',F8.2,5X,'PRINT INTERVAL =',F7.2,
     A 5X,'INTEGRATION STEP =',F7.3,//6X,'CONTROL INTERVAL MULTIPLE =',
     B I3,5X,'PLOT OPTION =',I2,5X,'INTEGRATION OPTION =',I2,
     C 5X,'IPUNCH =',I2)
```

```
      NOWS=1
      KPRINT=OUTT/DT+0.05
      KCOUNT=-1
      ICHK=0
      RRR=35.
      DTT=10.0D0*DT
      PSIPOL=DEXP(-.15*DTT)
      SAMRAT=0.0D0
      SIMPSI=0.0D0
          DUM1=0.0D0
      CC=15.
      SZERR=0.0
      SPHERR=0.0
      ZPOLE=1.0D0-0.01D0*DT
      PHPOLE=1.0D0-0.01*DT
      CALL INCOND(IDUM,UPRPM)
C
C
   60 KCOUNT=KCOUNT+1
      TIME=FLOAT(KCOUNT)*DT
C
C
C
      NOWS=NOWS+1
      IF(NOWS.EQ.301)NOWS=1
      IF(KCOUNT/KPRINT*KPRINT.NE.KCOUNT) GOTO111
   66 CALL OUTPUT
      J=JPLOT
      TRUDD=PRINT(9)
      SANG=PRINT(9)
        PLUN=PRINT(5)
        SPED=PRINT(2)
        R(J,1)=PRINT(9)
        R(J,2)=PRINT(4)
        R(J,3)=PRINT(5)
        R(J,4)=PRI(J,2)
        R(J,5)=PRI(J,3)
        R(J,6)=PRI(J,4)
      FRATE=PRI(J,9)
      FIR(J,1)=PRINT(12)
      FIR(J,2)=PRINT(9)
      SEC(J)=PRINT(10)
      THR(J)=PRINT(12)
      IF(ISTOUT.EQ.0)GO TO 524
  523 FORMAT(//,
```

```
      SUBROUTINE LINEF(X,S,RA,C,TIME,DT)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /STO/NSTOP
C    LINEF COMPUTES THE VALUE OF A FUNCTION, X, AND ITS SLOPE, S,
C    AT T=(TIME+DT) FROM A PEICEWISE LINEAR DESCRIPTION, RA(2,40).
C    RA(1,*) CONTAINS THE TIME-BREAK POINTS.
C    RA(2,*) CONTAINS THE FUNCTION VALUE AT THE TIME-BREAK POINT.
C    BEFORE RETURNING THE FUNCTION AND SLOPE ARE DIVIDED BY C. C.
C    X IS COMPUTED VALUE OF VARIABLE AT TIME+DT
C    S IS COMPUTED VALUE OF THE SLOPE AT TIME+DT
C
C    RA IS ARRAY CONTAINING BREAKPOINTS WHOSE ORDINATES ARE IN UNITS
C    WHICH MUST BE DIVIDED BY C TO GET APPROPRIATE UNITS FOR X.  IF
C    UNITS IN RA(2,*) ARE DEGREES, C SHOULD BE RADIAN.  IF UNITS IN
C     RA(2,*) ARE RPM, C SHOULD BE UNITY (CONE IN PROP1).
C
      DIMENSION RA(2,1)
      T=TIME+DT
C
C
      CC=1./C
C
      DO 10 I=2,NSTOP
      IF(T.LE.RA(1,I))GO TO 20
10    CONTINUE
      I=NSTOP
C
20    IM1=I-1
      S=CC*(RA(2,I)-RA(2,IM1))/(RA(1,I)-RA(1,IM1))
      X=CC*RA(2,IM1)+S*(T-RA(1,IM1))
C
C
C
C
C
C
C
C
C
      RETURN
      END
```

```
      SUBROUTINE AUTO(X,XD)
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      COMMON /PRIN2/OUTT,SZERR,ZPOLE,SZC,DRC,SPHERR,PHPOLE,DUM1,DUM2
      COMMON /PRIN4/CC,SAMRAT,PSIPOL,DTT,SIMPSI
      COMMON PADD(72),
     A DB(12),DS(12),DR(12),PROP(12),OFF(12),CLIP(10),
     B BLFG(2,20),SLFG(2,20),RLFG(2,20),PLFG(2,20),
     C BRI(6),ALFA(6),XT(6),TBLST(6),TBLSP(6),VT(6),VOL(6),
     D EPA,EDS,DPSID,DT,TIME,STOPTM,PAD(11),
     E NT,ICON(7),IREC(6),I1,INVOPT,ICHK,IPAD(5),NST
C
C
      DIMENSION X(1),XD(1)
      DIMENSION AB(5),BB(5),AS(5),BS(5)
      DATA AS/-1.5,-.2,0.,.2,1.5/,BS/-28.0,0.,0.,0.,28./
      DATA AB/-2.,-1.75,0.,1.75,2./,BB/-20.,0.,0.,0.,20./
      DATA CB1,CB2/.2,3./,CS1,CS2/.1,.5/
C
C
C
C
C AUTOMATIC FEEDBACK CONTROLAFOR BOW PLANE, STERN PLANE,
C RUDDER, AND RPM TO CONTROL DEPTH, PITCH, OFFTRACK,
C AND SPEED
C
C
C
 37   ICON1=ICON(1)
      IF(ICON(1).EQ.20)ICON1=ICON(1)/10
      X15=0.
      X16=0.
      N=TIME/OUTT+1.1
      IF(ICON(1).NE.20)GO TO 234
      SAMRAT=PSIPOL*SAMRAT+XD(9)*(0.150D0*CC-0.050D0)*DTT
      SIMPSI=CC*XD(9)-SAMRAT
      SIMPSI=DABS(SIMPSI)
      X16=RELAY(AS,BS,SIMPSI)
      AXD9=XD(9)*57.296
      AXD9=DABS(AXD9)
      X15=RELAY(AB,BB,AXD9)
      X16=X16/57.296
      X15=X15/57.296
 234  CONTINUE
      GO TO (10,10,50,10,10,50,10,10,80,10,10,50,10,10,50,10,10),ICON1
   10 THERR=DS(4) - X(8)
      ZERR = DB(4) - X(12)
      ZPOLE=0.950
         IF(TIME.LE.1.0)SZERR=0.0
      SZERR=ZPOLE*SZERR+ZERR
      DSORD = -DS(7) * THERR + DS(8) * XD(8)
       DBORD=-DB(7)*ZERR+DB(8)*XD(12)
      DSORD3=SZC*SZERR
      IF(ICON(1).EQ.20)DSORD=DSORD+DSORD3
      GO TO (20,30,50,20,30,50,20,30,80,20,30,50,20,30,50,20,30),ICON1
```

```
   20 DSORD = DSORD - DBORD
      GO TO 40
30    CONTINUE
      DDBDOT=(DBORD-X(15))*DB(9)
      IF (DABS(DDBDOT).GT.DB(2)) DDBDOT =DSIGN(DB(2),DDBDOT)
      XD(15)=DDBDOT
      X(15)=X(15)+DT*DDBDOT
C
      X(15)=X(15)+X15
      IF(DABS(X(15)).GT.DB(3))X(15)=DSIGN(DB(3),X(15))
C
   40 DDSDOT = (DSORD - X(16) ) * DS(9)
      IF  (DABS(DDSDOT).GT.DS(2)) DDSDOT =DSIGN(DS(2),DDSDOT)
      XD(16)=DDSDOT
      XL16=DT*DDSDOT
C

      DRC=X16*57.296
      X(16)=XL16+X16
      IF(DABS(X(16)).GT.DS(3))X(16)=DSIGN(DS(3),X(16))
C
      GO TO (90,90,50,50,50,50,50,50,80,80,80,50,050,050,50,050,050),ICO
     AN1
   50 PSIERR = DR(4) - X(9)
      DRORD = -DR(7) * PSIERR + DR(8) * XD(9)
      ONE=4.
      GO TO(90,90,70,70,70,60,60,60,80,80,80,70,70,70,60,060,060),ICONJ
   60 DRORD=DRORD-OFF(7)*(OFF(4)-X(11)) + OFF(8)*XD(11)
   70 DDRDOT = (DRORD - X(18) )  * DR(9)
      IF (DABS(DDRDOT).GT.DR(2)) DDRDOT =DSIGN(DR(2),DDRDOT)
      XD(18)=DDRDOT
      X(18)=X(18)+DT*DDRDOT
      IF(DABS(X(18)).GT.DR(3))X(18)=DSIGN(DR(3),X(18))
      IF(ICON(1).LT.9)GO TO 90
   80 XD(19)= (PROP(4) - X(1)/1.689)*PROP(7)
      X(19)=X(19)+DT*XD(19)
90    RETURN
      END
```