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GUNNER TRACKING BEHAVIOR AS A FUNCTION

OF THREE DIFFERENT CONTROL SYSTEMS
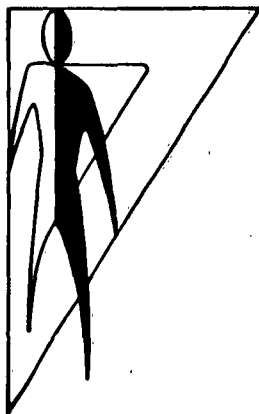
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HUMAN ENGINEERING LABORATORIES

ABERDEEN PROVING GROUND,
MARYLAND

GUNNER TRACKING BEHAVIOR AS A FUNCTION

OF THREE DIFFERENT CONTROL SYSTEMS

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ABSTRACT

An investigation was conducted to determine the
magnitude and character of tracking errors occurring
after firing a rocket at a moving target from a light-
weight mount. Six professional gunners with varying
degrees of experience fired 3.5-inch rockets from
each of three distinct types of tracking devices, viz.,
a two-Hand Wheel system, an electrical rate system, and
a viscously damped, integrated position control system
(Free Mount).

There was no significant difference in magnitude
of tracking error between the Free Mount and the rate
system, with both achieving 0.5 mils RMS error across
all conditions of angular rate. The two-Hand Wheel
system was significantly worse with 1.0 mils error
at low rates and 2.0 mils error at high rates.

CONTENTS

GUNNER TRACKING BEHAVIOR AS A FUNCTION

OF THREE DIFFERENT CONTROL SYSTEMS

INTRODUCTION

The accuracy of antitank weapon systems has been improved through the years by using high velocity or guided projectiles. However, the total system's effectiveness also depends on the gunner's accuracy -- whether for pointing a ballistic weapon, or for continuous tracking after firing a guided missile. For this reason, realizing these weapons' full effectiveness requires an investigation of the gunner's task.

A series of studies conducted by the U. S. Army Human Engineering Laboratories and reported in Technical Note 6-62, measured the accuracy with which gunners could track a moving target using conventional tracking systems, namely, 106mm Recoilless Rifle Mount M20, 155mm XM29 mount, 120mm XM89 mount, 105mm M112 mount, M-48 tank turret, and tripod-mounted machine gun.

The purpose of these studies was to measure the tracking error after firing a round to allow evaluation of how the mounts would work in a guided missile situation. Therefore, both the magnitude of the error and the frequency characteristics were important.

The M-48 tank turret permitted a degree of accuracy and smoothness at least twice as good as any of the other systems tested, thus indicating that accuracy with present ground mounts is not being limited by any innate limitation of human gunners but rather by the interaction of gunner and mount.

An effort to increase the accuracy of lightweight ground mounts was initiated in accordance with the recommendations of Technical Note 6-62. These five recommendations were:

a. Carry all three types of tracking systems -- i.e., rate, two-Hand Wheel, and Free Mount --to further development in order to correct the deficiencies noted in tests, within the limitations of weight and general configuration for a tactical mount.

b. Every possible consideration should be given to the tracking task for these mounts. Backlash, wind-up, and friction should be at a minimum. Mechanical tolerance of 0.1 mil (angular) on the output side for backlash and short-term (3 sec.) drift would be adequate, if attainable. Harmonic drive units might be considered as high efficiency, low backlash gear reducers.

c. Methods of smoothing out the oscillations should be considered, especially viscous damping, which is normally used in servo loops for this purpose. Little quantitative information is available on human characteristics; therefore, the optimum damping factor should be determined empirically.

d. To eliminate transients during firing, attention must be given to unbalanced or changing forces, especially in the Free Mount. Changing balance of the system can be avoided by locating the center of gravity of the round directly over the elevation trunnion. Firing torques due to small amounts of recoil can be avoided by having both pivoting axes pass through the bore axis.

e. These mounts should be tested at the same time using a counterbalanced order of presentation. Both experienced and novice gunners should be used in this test, because individual differences are still apparent with these systems.

The three mounts were to represent the best design for each of the three basic methods for two-dimensional control. One was the traditional two-Hand Wheel mount, but with a bare minimum of coulomb friction, backlash, and windup, and with the addition of a noticeable amount of viscous smoothing. The second mount was an integrated position control with a 1:1 control ratio, sometimes referred to as a "Free Mount", because its motion is unrestrained by gears, etc.

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Friction was negligible and considerable viscous damping was added. The third mount was a rate system using electric motors and a common form of a handle bar controller. The problem with this mount was in trying to design a great deal of quality into a lightweight field mount. A technical description of each of these mounts is given in Appendix A.

The purpose of this investigation was to determine the tracking accuracy and characteristics of the three mounts developed by the Human Engineering Laboratories, as a basis for estimating gunners' ability to perform with tactical tracking systems of similar design. The aspects considered were performance as a function of angular tracking rate, direction of tracking, and individual differences.

METHOD

Six gunners were selected for this test. One gunner was an expert with rate tracking, and one an expert with two-Hand Wheel tracking; but, because the Free Mount is a relatively new type of system, there were no available experts at using it. The two expert subjects were selected by previous test results as well as experience and reputation. The other four gunners had little or no experience with tracking.

The test was conducted on a triangular target course of 3000 meters perimeter. Firing was conducted from inside the triangle toward one of the legs. The crossover range was 500 meters.

The target was a 7½' x 7½' square target which had an eight-inch-wide vertical cross to clearly indicate its center. It was mounted on a self-propelled, radio-controlled railroad cart, which moved in both directions at speeds of 5 mph and 30 mph, as commanded.

The three test mounts described in Appendix A were used to track the target. An M-20A1B1 3.5 inch Rocket Launcher was fixed to each weapon and the gunners fired an M29A2 practice rocket during each run. This rocket was used to simulate a firing environment and cause a slight perturbation in the mount which the gunner must correct quickly, rather than with the idea that the gunners should hit the target.

TABLE 1

Order of Presentation for
Subjects 1, 2, 3, 4, 5, and 6

Trial	Subject	Mount*	Direction**	Speed (mph)
1	1	A	L	5
2	1	A	R	5
3	1	A	L	30
4	1	A	R	30
5	2	A	L	5
6	2	A	L	30
7	2	A	R	5
8	2	A	R	30
9	3	B	L	5
10	3	B	L	30
11	3	B	R	5
12	3	B	R	30
13	4	B	R	5
14	4	B	R	30
15	4	B	L	5
16	4	B	L	30
17	1	B	L	5
18	1	B	L	30
19	1	B	R	5
20	1	B	R	30
21	5	C	L	5
22	5	C	L	30
23	5	C	R	5
24	5	C	L	30
25	6	C	L	5
26	6	C	L	30
27	6	C	R	5
28	6	C	R	30
29	3	C	L	5
30	3	C	L	30
31	3	C	R	5
32	3	C	R	30
33	4	C	L	5
34	4	C	L	30
35	4	C	R	5
36	4	C	R	30
37	1	C	L	5
38	1	C	L	30
39	1	C	R	5
40	1	C	R	30
41	2	C	L	5
42	2	C	L	30
43	2	C	R	5
44	2	C	R	30
45	5	A	L	5
46	5	A	L	30
47	5	A	R	5
48	5	A	R	30
49	6	A	L	5
50	6	A	L	30
51	6	A	R	5
52	6	A	R	30
53	3	A	L	5
54	3	A	L	30
55	3	A	R	5
56	3	A	R	30
57	4	A	L	5
58	4	A	L	30
59	4	A	R	5
60	4	A	R	30
61	2	B	R	5
62	2	B	R	30
63	2	B	L	5
64	2	B	L	30
65	5	B	R	5
66	5	B	L	30
67	5	B	R	30
68	5	B	L	30
69	6	B	R	5
70	6	B	L	5
71	6	B	L	30
72	6	B	R	30

*Mounts: A - Rate, B - Free, C - Hand Wheel.

**Direction: L - from left to right
             R - from right to left.

Data were collected with a 16mm boresighted gun camera operating at 24 frames per second. It was equipped with a mil-scale reticle for ease of data reduction (see Appendix B). On each trial the camera operated from several seconds before firing until ten seconds after firing. A tare strip exposed at a stationary target before testing measured boresight error.

PROCEDURE

A partially counterbalanced order of presentation was chosen to reduce differential transfer of training between mounts. However, for test simplicity and to reduce the possibility of negative transfer effects between mounts, each subject took all of his trials with a mount at the same time. A gunner had four shots for each mount: one in each direction, at each of two speeds (5 mph and 30 mph). The resulting order of presentation is shown in Table 1.*

Each subject was given 15 minutes of tracking practice with each mount just before his four trials for record. Although this certainly did not amount to an extensive training program, the intent of the test was to assess the need for training by comparing the results of the experts with those of the relatively untrained gunners.

On the firing trials the gunner was instructed to track the target as accurately as he could before and for at least ten seconds after pulling the trigger.

All gunners wore ear defenders and face shields (as shown in Figure 1) to protect themselves from the rocket noise and back blast.

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*Some deviation from the original intent is obvious. This was due to expediencies taken in the field to overcome equipment malfunctions.

Fig. 1. GUNNER PROTECTION

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RESULTS

Backlash developed during the testing program in both the Rate
Mount and the Hand Wheel Mount. In the rate azimuth loop the
problem was overcome by adding spring tension where the changing
load was compensated by tachometer feedback. This method could not
be used with the Hand Wheel Mount. In both cases an inspection of the
results did not indicate any systematic chronological error source
that could be attributed to backlash and, therefore, the results were
accepted without modification or reservation. The Free Mount also
received a minor adjustment during the test, as discussed in detail on
page 32.

The data films were developed and projected in the normal manner
and, using the grid reticle on the film, it was possible to read
azimuth and elevation errors to approximately 0.1 mils (equal to one
decimeter at 1000 meters). The data were sampled for all trials from
one second before firing until 10 seconds after firing (unless the camera
had stopped at nine seconds), reading every eighth frame of tracking
(or three frames per second). The RMS (root-mean-square, or standard
deviation) was obtained for each second. These results are presented
in Tables 2, 3, 4, 5, 6,and 7, along with the RMS values for the last
nine seconds, the last seven seconds, and various totals as shown.*

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  The data under "mean" are the algebraic sum of data with plus being
high and to the right. For horizontal errors the sign was corrected
for tracking direction and reported as "lead." These numbers were not
used in any calculation but only serve as an indication of fixed
tracking bias and a check on boresight malalignment. A visual inspec-
tion indicates the totals were quite small (approximately 0.1 mils),
leading to the conclusion that the data are distributed about the
target center except at high angular rate with the Hand Wheel Mount.
In this case, the 0.75 mil lag indicates an inability of the gunners
to keep up with the target movement.

TABLE 2

Free Mount – Vertical Error

| | Direction | Speed | | Seconds of Tracking | | | | | | | | | | | Last | | |
Run	From	mph	Gunner	-1	1	2	3	4	5	6	7	8	9	10	9	7	Mean
9	L	5	3	.11	2.33	1.59	1.01	.49	.50	.36	.48	.16	.32	.16	.71	.37	+.06
10	L	30	3	.16	2.44	1.65	.32	.20	.40	.17	.53	.14	.13	.26	.62	.30	-.02
11	R	5	3	.14	3.95	.71	.24	.26	.16	0	.17	.20	.24	.33	.32	.22	-.13
12	R	30	3	.50	.61	.85	.16	.20	.24	.28	.26	.26	.41	.28	.37	.28	-.18
13	R	5	4	.10	2.21	.71	.20	.36	.32	.17	.20	.20	.11	.16	.32	.22	-.24
14	R	30	4	.33	2.64	1.28	.68	.16	.14	.16	.11	.08	.22	.14	.50	.14	-.19
15	L	5	4	.16	1.56	1.14	.06	.08	.08	.06	.06	.13	.14	—	.41	.10	+.13
16	L	30	4	.48	.71	.24	.16	.26	.17	.22	.16	.32	.48	—	.26	.28	-.16
17	L	5	1	.13	2.54	2.02	.16	.50	.14	.17	.13	.11	.13	.17	.71	.22	-.08
18	L	30	1	.08	.32	.20	.33	.17	.13	.13	.13	.06	.06	.08	.17	.11	-.12
19	R	5	1	0	1.62	.32	.28	.28	.16	.16	.11	.22	.22	—	.22	.20	-.20
20	R	30	1	.24	.61	.28	.24	.30	.06	.13	.14	.08	.17	.14	.19	.16	-.08
61	R	5	2	0	1.12	.88	.45	.39	.30	.14	.24	.16	0	—	.40	.24	+.08
62	R	30	2	.24	1.46	.77	.44	.24	.06	.22	.13	.32	.24	.28	.36	.22	-.05
63	L	5	2	.22	.81	.44	.57	.24	.33	.24	.47	.22	.68	.32	.43	.39	-.27
64	L	30	2	.36	1.29	.47	.58	.20	.22	.50	.24	.26	.39	.24	.37	.31	-.17
65	R	5	5	.13	2.21	.58	.22	.17	.08	.20	.13	0	.22	.13	.24	.14	-.10
66	L	5	5	.24	3.07	1.68	.10	.50	.22	.37	.08	.16	.20	—	.65	.29	-.25
67	R	30	5	0	1.35	.44	.36	.39	.11	.14	.20	.16	.17	.13	.28	.20	-.10
68	L	30	5	.13	1.12	.16	.20	.13	.45	.22	.16	.22	.14	.30	.24	.25	-.16
69	R	5	6	.42	.69	1.63	.32	.26	.26	.56	.17	.28	.19	—	.65	.32	-.04
70	L	5	6	.33	3.33	2.17	.76	.24	.37	.22	.32	.06	.24	.45	.81	.30	-.20
71	L	30	6	—	1.66	.99	2.25	.55	.57	.68	.47	2.83	2.03	.61	1.49	1.40	-.40
72	R	30	6	.78	3.03	.42	.71	.19	.24	.46	.54	.22	.59	.59	.46	.41	-.24
TOTAL RMS				.29	2.02	1.08	.63	.31	.28	.28	.28	.61	.50	.30	.54	.39	-.13

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TABLE 3

Free Mount – Horizontal Error

Run	Direction From	Speed mph	Gunner	-1	1	2	3	4	5	6	7	8	9	10	Last 9	Last 7	Mean	Lead
9	L	5	3	.85	5.94	2.57	1.34	.31	.75	.44	.62	.17	.18	.75	1.05	.51	+.30	+.30
10	L	30	3	1.84	8.01	2.51	1.01	.52	.90	.48	.37	.54	.49	.72	1.04	.60	+.09	+.09
11	R	5	3	.17	6.01	2.96	1.12	.52	.44	.49	.20	.33	.32	.54	1.12	.42	+.18	-.18
12	R	30	3	.20	3.83	1.72	.66	.24	.26	.16	.26	.36	.36	.28	0.64	.28	0	0
13	R	5	4	.37	1.74	1.16	.49	.42	.54	.17	.30	.50	.31	.29	.54	.38	+.20	-.20
14	R	30	4	.52	1.11	.54	.79	.71	.88	1.04	.74	.58	.78	.49	.76	.77	-.49	+.49
15	L	5	4	.06	1.45	.71	.78	.10	.13	.72	.47	.71	.41		.77	.49	-.12	-.12
16	L	30	4	1.17	9.56	.63	.51	.24	.29	.39	.46	.33	.12		.39	.32	-.12	-.12
17	L	5	1	.32	2.08	1.63	1.48	.79	.40	.14	.26	.05	.17	.34	.79	.38	+.30	+.30
18	L	5	1	.35	1.33	1.51	1.11	.42	.63	.33	.12	.29	.35	.34	.69	.38	+.16	+.16
19	R	5	1	.25	.21	.73	.13	.59	.51	.38	.45	.51	.56		.50	.51	+.30	+.30
20	R	30	1	.26	.74	1.33	.75	.71	.77	.52	.36	.91	.76	.52	.78	.67	+.61	+.61
61	R	5	2	.37	1.21	.81	.86	.59	.46	.86	.55	.56	.58	.17	.68	.62	+.01	-.01
62	R	30	2	.14	.17	.54	.33	.70	.39	.26	.50	.58	.33	.67	.45	.45	-.20	+.20
63	L	5	2	.17	1.82	.10	.56	.30	.36	.33	.71	.62	.55	.49	.50	.53	-.24	-.24
64	L	30	2	.24	2.41	1.10	.79	.17	.60	.22	.70	.48	.22		.60	.46	-.40	-.40
65	R	5	5	.08	1.35	.48	.24	.08	.29	.17	.29	.31	.17	.17	.26	.22	-.16	+.16
66	L	5	5	.69	.92	.17	.20	.11	.10	.17	.30	.24	.22		.20	.19	-.14	-.14
67	R	30	5	.08	.92	.33	.26	.35	.05	.24	.33	.71	.47	.16	.38	.39	+.07	-.07
68	L	30	5	.46	1.86	.35	.20	.24	.47	.17	.79	.58	.17	.17	.40	.41	-.21	-.21
69	R	5	6	.13	.50	.42	.58	.77	.30	.30	.46	.08	.11	.26	.44	.41	+.27	-.27
70	L	5	6	.26	2.37	.70	.65	.62	.20	.20	.37	.16	.42	.93	.44	.35	0	0
71	L	30	6		3.42	1.05	1.00	.81	.33	.71	.93	1.81	1.64		1.11	1.13	-.70	-.70
72	R	30	6	.62	.74	.14	.52	.24	.16	.22	.71	.53	.26	.40	.40	.40	-.12	+.12
TOTAL RMS				.58	3.48	1.31	.82	.50	.49	.45	.51	.61	.52	.48	.68	.51	-.14	-.21

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TABLE 4

Rate Mount – Vertical Error

Run	Direction From	Speed mph	Gunner	-1	1	2	3	4	5	6	7	8	9	10	Last 9	Last 7	Mean
1	L	5	1	.20	.83	.08	0	.16	.34	.21	.17	.17	.17	0	.17	.19	-.12
2	R	5	1	.14	.69	.17	.24	.24	.14	0	0	.07	.10	—	.15	.12	-.12
3	L	30	1	.13	1.00	.11	.11	.24	.07	.21	.21	.06	.13	.26	.17	.18	-.12
4	R	30	1	.14	.08	.14	.10	.14	.10	.17	.41	.68	.39	—	.33	.37	-.12
5	L	5	2	.20	.87	.24	.13	.58	.54	.41	.17	0	.17	—	.35	.37	-.10
6	L	30	2	.08	.98	.66	.45	.17	.33	.17	0	.06	.10	—	.32	.17	+.23
7	R	5	2	.06	4.55	.16	.20	.06	.13	.20	.08	0	0	—	.13	.10	+.02
8	R	30	2	.17	1.56	.26	.16	.39	.08	.06	.14	0	.11	—	.19	.18	+.13
45	L	5	5	.06	1.02	.70	.84	.73	.70	.51	.17	.17	.20	0	.49	.45	+.30
46	L	30	5	.14	.87	.33	.20	.13	.20	.17	.06	.06	.14	.08	.17	.14	-.09
47	R	5	5	0	1.24	.11	.14	.10	0	0	0	.06	.10	.08	.08	.02	-.003
48	R	30	5	.17	1.22	.31	.06	.20	.26	.17	.08	.08	.20	.20	.19	.17	+.11
49	L	5	6	0	.74	.41	.24	.13	.10	.10	.14	.20	.20	.06	.20	.14	-.17
50	L	30	6	.24	.81	.54	.62	.45	.24	.20	.13	.17	.16	.06	.35	.22	+.11
51	R	5	6	.22	.81	.54	.49	.45	.17	.17	.13	.14	.16	.11	.31	.21	-.10
52	R	30	6	.24	.91	.60	.57	.47	.20	.20	.13	.14	.17	—	.35	.24	-.09
53	L	5	3	.10	.32	.36	0	.10	.08	.16	.30	.20	.20	.16	.20	.14	+.07
54	L	30	3	.17	.72	.73	.77	.28	.29	.06	.16	.20	.06	—	.41	.22	-.13
55	R	5	3	.10	.87	.06	.14	.10	.06	.06	0	.17	0	—	.09	.09	-.05
56	R	30	3	.16	1.10	.56	.24	.06	.16	.17	0	.10	.24	.30	.24	.17	+.12
57	L	5	4	.14	.84	0	0	.35	.33	.24	.20	.08	0	—	.20	.18	+.14
58	L	30	4	.22	1.04	.40	.77	.16	.24	.16	.14	0	.08	.08	.32	.19	+.08
59	R	5	4	.14	.34	.16	0	.06	.16	.20	.20	.20	.06	0	.14	.09	+.08
60	R	30	4	.16	.40	.71	.56	.32	.55	.71	.22	.20	.81	—	.56	.53	+.33
RMS				.15	1.28	.41	.40	.31	.28	.24	.17	.19	.22	.14	.28	.23	+.02

TABLE 5

Rate Mount – Horizontal Error

Run	Direction From	Speed mph	Gunner	Seconds of Tracking											Last		Mean	Lead
				-1	1	2	3	4	5	6	7	8	9	10	9	7		
1	L	5	1	.51	.45	.53	.59	.46	.41	.19	.42	.29	.84	.60	.49	.49	+.12	+.12
2	R	5	1	.08	1.11	1.09	.34	.14	.08	.14	.08	.29	.10		.42	.16	-.05	+.05
3	L	30	1	.35	.13	.48	.42	.24	.17	.76	1.30	.34	1.10	.66	.71	.77	-.50	-.50
4	R	30	1	.18	.26	.29	.51	.21	.41	.25	.97	.42	.18		.49	.49	+.22	-.22
5	L	5	2	.26	.64	1.22	1.07	1.31	.31	.24	.12	.26	.13		.76	.57	-.40	-.40
6	L	30	2	.91	.08	.13	1.01	.10	.50	.29	.42	.23	.29		.50	.33	-.05	-.05
7	R	5	2	.57	.86	.41	.37	.24	.61	.20	.16	.51	.31		.38	.38	-.01	+.01
8	R	30	2	.24	.40	.70	1.09	.62	.24	.29	.31	.41	.71		.61	.46	+.08	-.08
45	L	5	5	.36	.22	.59	.93	.69	.40	.88	.33	.14	.14	.32	.57	.49	-.32	-.32
46	L	30	5	.57	1.17	1.00	.20	.05	.11	.14	.20	.10	.17		.37	.14	-.03	-.03
47	R	5	5	.50	.20	.62	.81	.08	.10	.24	.44	0	.35	.03	.40	.24	-.19	+.19
48	R	30	5	.51	.26	.35	.33	.24	.36	.17	.20	.08	.13	.05	.24	.20	+.02	-.02
49	L	5	6	.36	.72	1.06	.87	.36	.26	.24	.10	.50	.37	.50	.56	.36	+.01	+.01
50	L	30	6	.99	.82	2.95	.56	2.71	1.16	.36	.28	.13	.08	.36	1.42	1.14	-.12	-.12
51	R	5	6	.92	.57	3.01	1.24	2.32	1.19	.39	.31	.13	.08	.36	1.41	1.02	-.18	+.18
52	R	30	6	.36	.86	3.01	1.29	2.71	1.21	.41	.28	.13	.08	.36	1.49	1.15	-.18	+.1
53	L	5	3	.06	.65	.30	.54	.87	.44	0	.17	.39	.40	.39	.45	.45	-.20	-.20
54	L	30	3	.08	1.29	1.20	.37	.59	.48	.35	.11	.13	.22		.54	.36	-.11	-.11
55	R	5	3	.39	.13	.41	.22	.17	.20	.26	.08	.44	.24		.28	.25	-.07	+.07
56	R	30	3	.39	.14	.18	.37	.22	.29	.12	.27	.18	.22	0	.23	.21	+.04	-.04
57	L	5	4	.31	.25	.58	.50	.29	.44	.14	.24	.13	.10		.35	.25	-.07	-.07
58	L	30	4	.76	.48	.55	.45	1.07	.37	.26	.18	.24	.56	.31	.51	.52	-.09	-.09
59	R	5	4	.14	.31	.34	.00	.08	.13	.20	.18	.06	.06	.08	.16	.12	+.10	-.10
60	R	30	4	.22	.19	.57	.12	.94	.85	.18	.44	1.14	.62		.69	.77	+.37	-.37
TOTAL RMS				.49	.62	1.24	.69	1.05	.56	.34	.42	.36	.41		.68	.58	-.06	-.09

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TABLE 6

Hand Wheel Mount – Vertical Error

Run	Direction From	Speed mph	Gunner	-1	1	2	3	4	5	6	7	8	9	10	Last 9	Last 7	Mean
21	L	5	5	.13	1.35	2.17	.20	.24	.11	.08	.17	.14	.06	.06	.73	.14	-.24
22	L	30	5	.06	1.26	.73	.45	.16	.13	.08	.06	0	.13	.10	.30	.10	-.06
23	R	5	5	.20	.41	.56	.17	.10	.10	.17	.10	0	0	.11	.22	.10	-.14
24	R	30	5	.08	.48	.16	.14	.06	0	.08	0	0	0	0	.08	.01	-.01
25	L	5	6	.17	.81	.60	.50	.50	.14	.20	.10	.10	.10	.06	.32	.22	-.11
26	L	30	6	.20	.37	1.75	.93	.19	.17	.13	.08	.06	.10	.10	.67	.12	-.21
27	R	5	6	.06	1.13	1.38	1.61	.53	.24	.20	.10	.10	.10	—	.78	.26	-.51
28	R	30	6	.26	.78	.67	1.06	.35	.22	.20	.20	.20	.24	.06	.46	.22	+.10
29	L	5	3	.14	.48	.11	.10	.17	.17	.08	.20	.17	.13	.30	.17	.18	-.003
30	L	30	3	1.34	1.13	3.20	2.66	.90	.41	.13	.06	.06	.24	.79	1.45	.49	+.06
31	R	5	3	.14	.08	.37	.39	.06	.10	.08	.10	.14	.08	.08	.20	.09	-.01
32	R	30	3	--	--	1.43	.45	.11	.10	.08	0	.08	0	.14	.51	.24	-.21
33	L	5	4	.20	.49	.26	.51	.33	.20	.20	.20	.14	.17	.17	.26	.20	-.03
34	L	30	4	.06	.51	1.36	.44	.50	.71	.95	.94	.32	.20	.26	.73	.62	-.35
35	R	5	4	.06	1.24	1.45	1.44	.58	.28	.10	.17	.14	.20	.17	.72	.26	-.48
36	R	30	4	.20	.81	.98	.06	.05	.08	.10	.08	.06	.08	.06	.33	.07	-.11
37	L	5	1	0	.61	.50	.50	.20	.17	.36	.17	0	.14	.17	.30	.20	-.09
38	L	30	1	.17	.42	.57	.65	.10	.10	.14	.14	.08	.17	.17	.32	.14	-.21
39	R	5	1	.20	.32	0	.06	.06	.17	.14	.08	.08	0	.06	.08	.10	-.05
40	R	30	1	.20	.14	.10	.14	.20	.20	.36	.20	.20	.20	.20	.21	.22	-.11
41	L	5	2	.20	1.35	2.30	1.36	1.14	.94	.40	.17	.10	.10	.06	1.03	.58	-.73
42	L	30	2	.20	1.61	2.29	1.17	.57	.17	.14	.06	0	.13	.50	.90	.26	-.45
43	R	5	2	.20	.81	.56	.20	.20	.20	.24	.33	.20	.30	.20	.29	.24	-.26
44	R	30	2	.20	1.44	.90	.41	.30	.20	.20	.17	.17	.10	.13	.37	.20	-.28
TOTAL RMS				.33	.89	1.13	.89	.41	.30	.26	.24	.13	.14	.24	.53	.26	-.20

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TABLE 7

Hand Wheel Mount -- Horizontal Error

Run	Direction From	Speed mph	Gunner	-1	1	2	3	4	5	6	7	8	9	10	Last 9	Last 7	Mean	Lead
21	L	5	5	.60	.70	2.02	1.21	1.33	1.19	.79	.30	.68	.48	.79	1.09	.86	+.15	+.15
22	L	30	5	1.02	1.56	2.81	3.88	.91	1.21	.97	.88	1.82	.89	.86	1.88	1.72	+.08	+.08
23	R	5	5	.77	2.08	3.16	2.98	1.24	.59	.41	.49	.47	1.12	.44	1.59	.76	-.28	+.28
24	R	30	5	1.68	.42	1.21	1.21	1.44	.83	1.42	1.26	2.13	1.48	.61	1.35	1.39	+.44	-.44
25	L	5	6	1.24	1.98	9.50	6.56	.75	1.61	.79	.37	.32	.00	.38	3.90	.77	+1.43	+1.43
26	L	30	6	1.39	7.74	5.25	8.80	2.56	4.05	3.15	2.82	1.80	.82	1.05	4.22	2.56	+.12	+.12
27	R	5	6	.58	1.83	1.57	1.35	1.37	.14	.41	.26	.47	.86		.96	.72	-.05	+.05
28	R	30	6	3.22	2.01	2.98	.61	2.54	.61	1.18	1.89	.37	1.93	1.43	-1.73	1.59	+.02	-.02
29	L	5	3	.93	.68	1.41	.74	1.40	1.02	.76	1.22	1.90	1.79	.93	1.31	1.35	-1.07	-1.07
30	L	30	3	.96	3.89	1.24	2.59	2.76	2.88	4.70	2.98	2.50	1.07	1.56	2.70	2.85	-1.98	-1.98
31	R	5	3	.67	.66	.82	.62	1.02	1.02	1.02	.83	.53	1.26	.96	.92	.97	+.76	-.76
32	R	30	3			2.30	2.60	2.66	3.76	1.57	1.15	2.73	1.48	1.60	2.34	2.31	+1.74	-1.74
33	L	5	4	.66	1.96	1.68	1.08	1.73	.51	.65	.75	1.37	1.16	.53	1.14	1.05	-.92	-.92
34	L	30	4	1.07	4.44	3.60	2.72	3.73	3.00	1.85	2.08	1.81	1.87	2.05	2.70	2.44	-2.01	-2.01
35	R	5	4	1.02	2.98	2.78	1.87	1.60	2.08	1.62	1.38	1.09	.37	1.11	1.68	1.41	+1.03	-1.03
36	R	30	4	1.08	2.66	4.08	1.56	1.50	2.22	1.49	1.44	1.09	2.46	.90	2.07	1.67	+1.35	-1.35
37	L	5	1	.79	.87	1.98	.61	.34	.80	.61	2.09	.59	.22	.25	.93	.92	-.36	-.36
38	L	30	1	1.88	.71	2.45	3.28	.83	.93	.67	1.76	4.90	3.03	2.23	2.58	2.48	-.42	-.42
39	R	5	1	.92	1.99	.97	.72	.87	1.24	.57	.25	.56	.13	.34	.71	.67	+.45	-.45
40	R	30	1	1.60	2.61	1.33	1.59	1.08	.76	1.44	1.27	.72	1.85	.99	1.27	1.22	+.99	-.99
41	L	5	2	.72	1.33	.81	3.84	4.21	1.42	2.38	1.00	.87	.75	.97	2.22	2.02	+.65	+.65
42	L	30	2	2.08	4.82	1.31	1.92	1.77	1.85	1.10	2.54	1.85	.92	.86	1.64	1.66	+.36	+.36
43	R	5	2	.39	.73	.58	.90	.52	.17	.67	.47	.51	.55	.00	.55	.47	+.41	-.41
44	R	30	2	1.49	4.60	3.57	2.58	1.46	1.02	1.38	1.27	.88	.60	1.43	1.80	1.19	+.64	-.64
TOTAL RMS		5		.78	1.66	3.20	2.54	1.43	1.11	1.04	.96	.89	.89	.70	1.63	1.02	+.18	-.20
		30		1.73	3.64	2.77	3.43	1.97	1.57	2.05	1.89	2.21	1.68	1.38	2.19	1.84	+.11	-.75

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Fig. 2. TRACKING PERFORMANCE IN FEET AS A FUNCTION OF TIME - FREE MOUNT

*Assuming 200 meter per second velocity.
O RMS Data
── Steady State Error

Feet off line of sight

Seconds
1000*
Meters

2000*
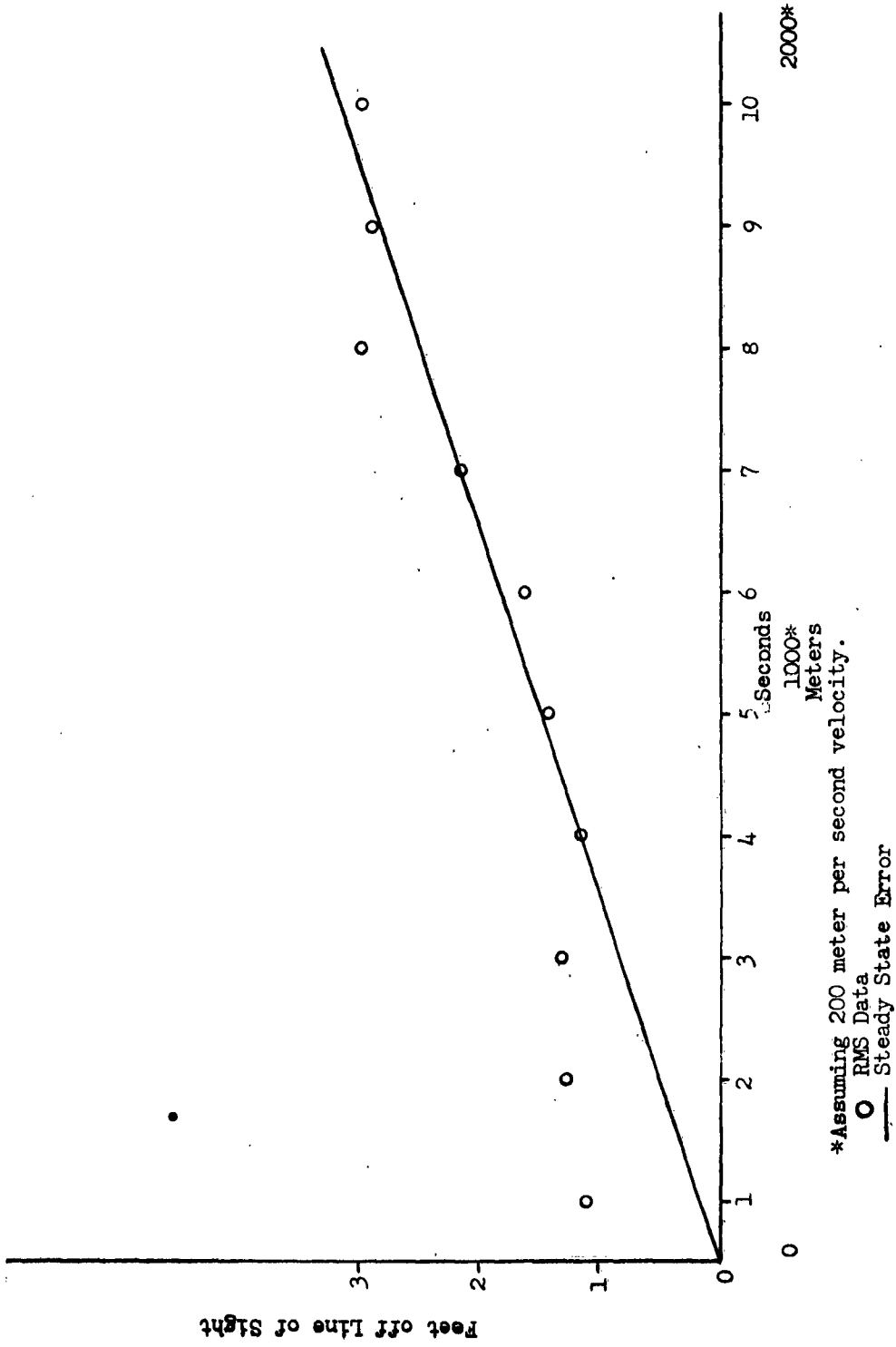
CONCLUSIONS

Inspection of these results indicates the following primary relationships (these statements are supported by an analysis contained in Appendix C):

a. There is no significant difference between the scores of the Free Mount and the Rate Mount.

b. The Hand Wheel Mount is significantly less accurate than either of the other two.

c. Angular tracking rate had no significant effect on the performance of either the Rate Mount or the Free Mount, but caused a significant change in performance with the Hand Wheel Mount. (Although no attempt was made to counterbalance training effects with angular tracking rate presentation, the higher rates came last, and increases in error overrode any effect of training.)

d. The difference in performance as a function of tracking direction is ambiguous, because the better performance came last and therefore could be easily attributed to training.

It is possible to interpret the angular error scores in terms of feet off the line of sight at any range by specifying a missile velocity. This has been done on Figures 2, 3, and 4, by assuming a 200 meter per second velocity and multiplying the RMS error for each second by the average range for that second. Inspection of these figures indicates that the initial excursion is not important in terms of feet off the target center. The straight line on these figures is an approximation of the steady-state error. The data dots show how quickly the systems recovered from the firing induced transient. The Free Mount has recovered in four seconds, the Rate Mount in six seconds, and the Hand Wheel Mount in seven seconds. (Because of the poor performance of the Hand Wheel Mount, selective data were presented in Figure 4.)

In order to clearly see the dynamic characteristics of the tracking error, four trials with each weapon were carried to a further stage of reduction. They were selected by rank-ordering the horizontal results for the last nine seconds of tracking for each weapon and at each
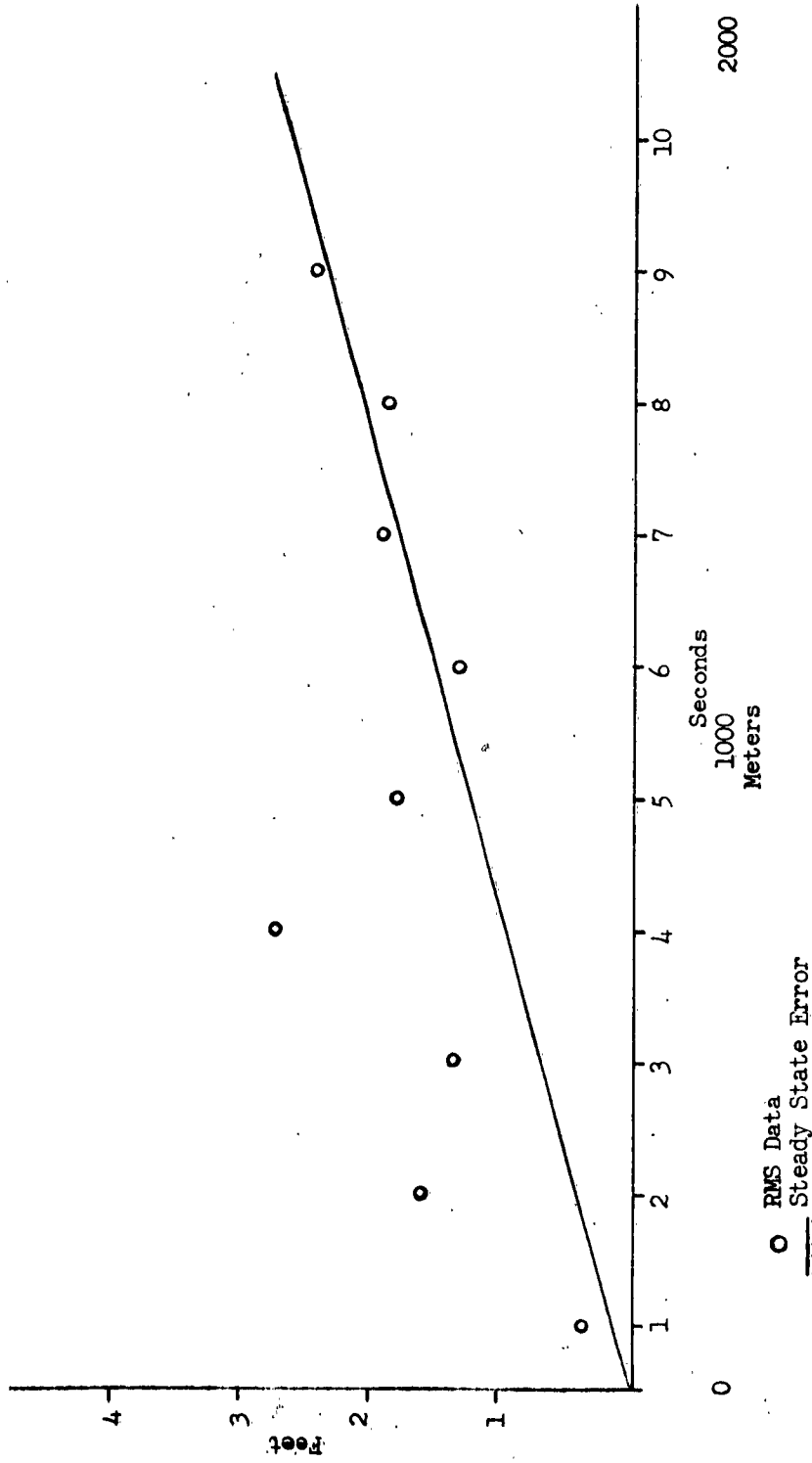
15

Fig. 3. TRACKING PERFORMANCE IN FEET AS A FUNCTION OF TIME – RATE MOUNT

o RMS Data
— Steady State Error

16

Fig. 4. TRACKING PERFORMANCE IN FEET AS A FUNCTION OF TIME – HAND WHEEL MOUNT

O RMS Data

—— Steady State Error

17
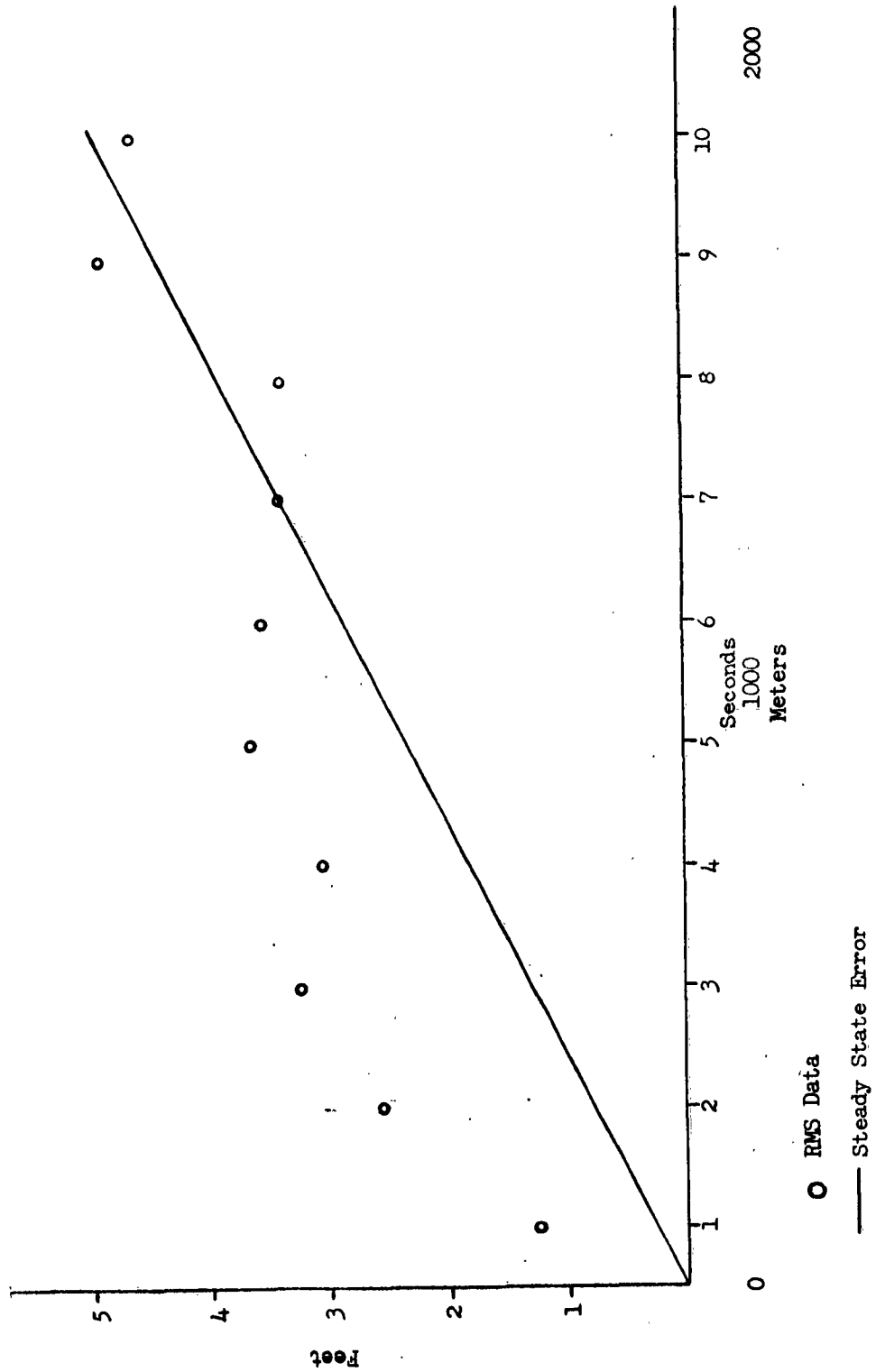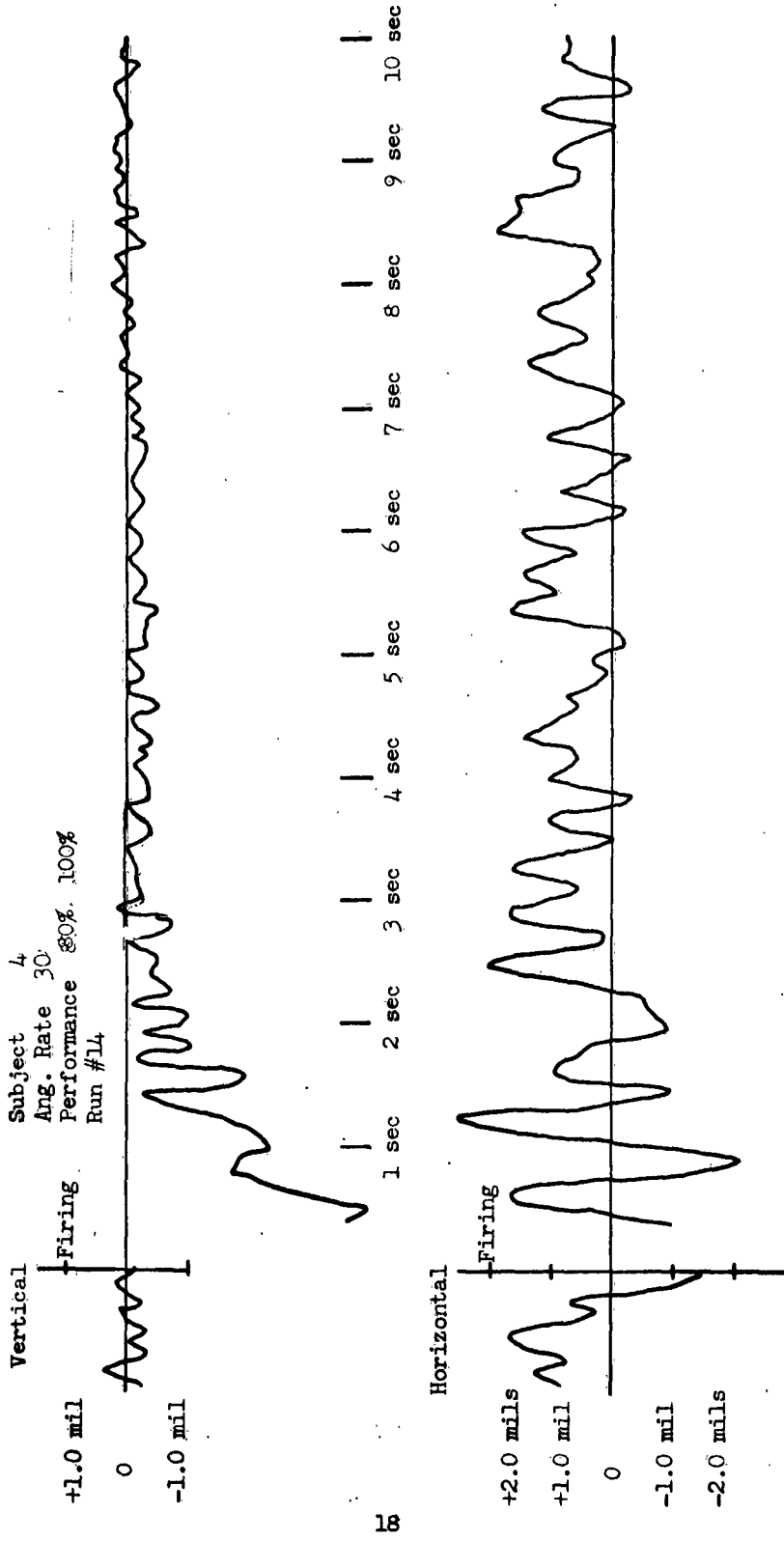
Fig. 5. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – FREE MOUNT

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angular tracking rate. The fourth and ninth best trials under each of these conditions were read on an x-y viewer for every other frame, or twelve frames per second. These results were subsequently plotted as time traces and are presented in Figures 5 through 16. In addition, an RMS was obtained for each of these more precise results, for comparison with the previous results. The loss of precision from sampling was found to be less than 0.1 mil.

The time traces can be interpreted further by comparing them to a target time curve for a 200 meter per second missile shown in Figure 17.

This analyses has been done for the error traces shown, including the time-on-target measures reported as performance for azimuth and elevation respectively in Figures 5 through 16.

Vertical

Subject 4
Ang. Rate 5
Performance 100%, 100%
Run #15

+1.0 mil

0

-1.0 mil

1 sec 2 sec 3 sec 4 sec 5 sec 6 sec 7 sec 8 sec 9 sec 10 sec

Horizontal

+2.0 mils

+1.0 mil

0

-1.0 mil

-2.0 mils

Fig. 6. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – FREE MOUNT

Vertical

Subject 6
Ang. Rate 5
Performance 100%, 100%
Run #70

+2 mils
+1 mil
0
-1 mil
-2 mils
-3 mils
-4 mils
-5 mils

Horizontal

+3 mils
+2 mils
+1 mil
0
-1 mil
-2 mils

1 sec 2 sec 3 sec 4 sec 5 sec 6 sec 7 sec 8 sec 9 sec 10 sec
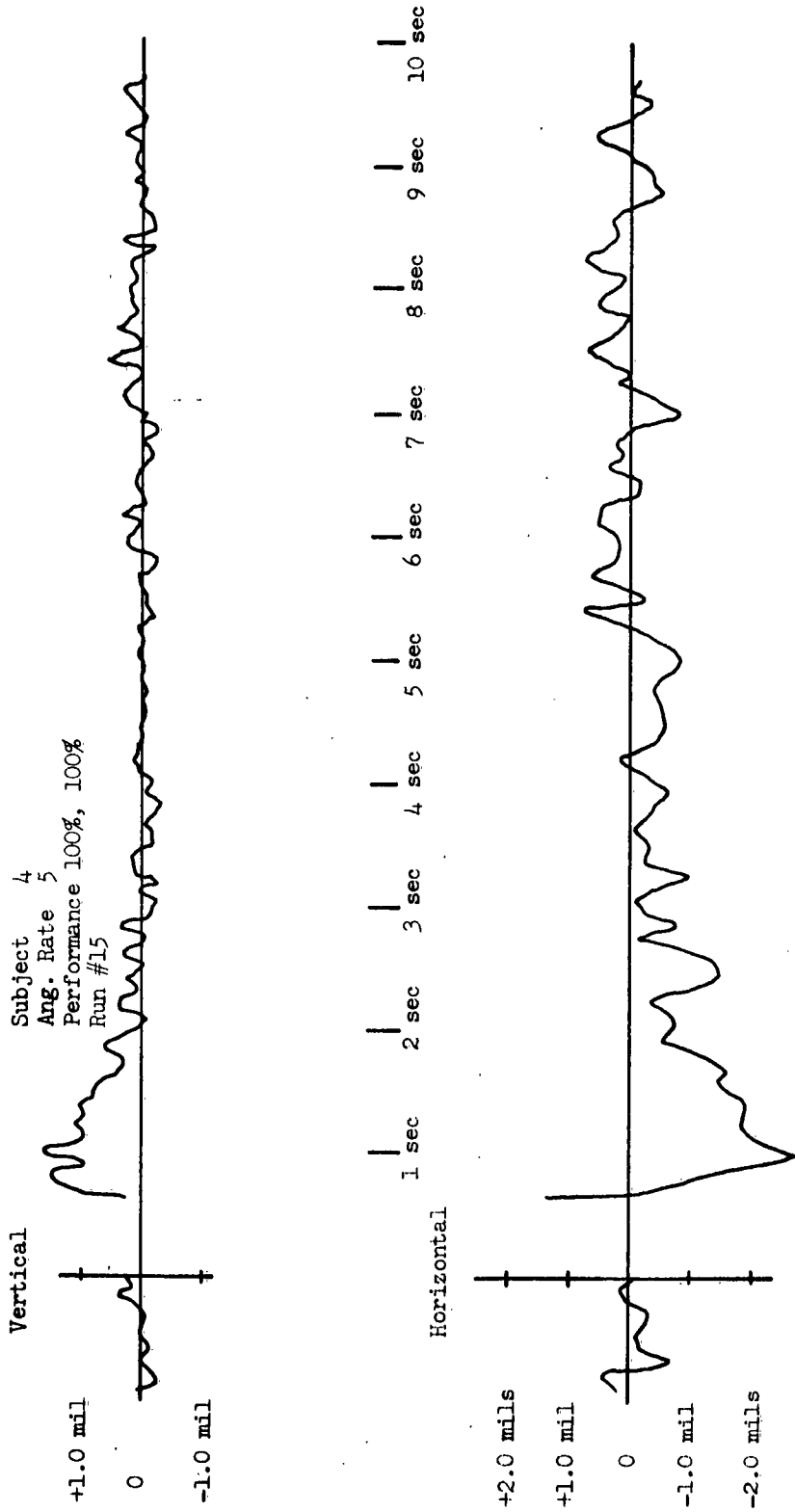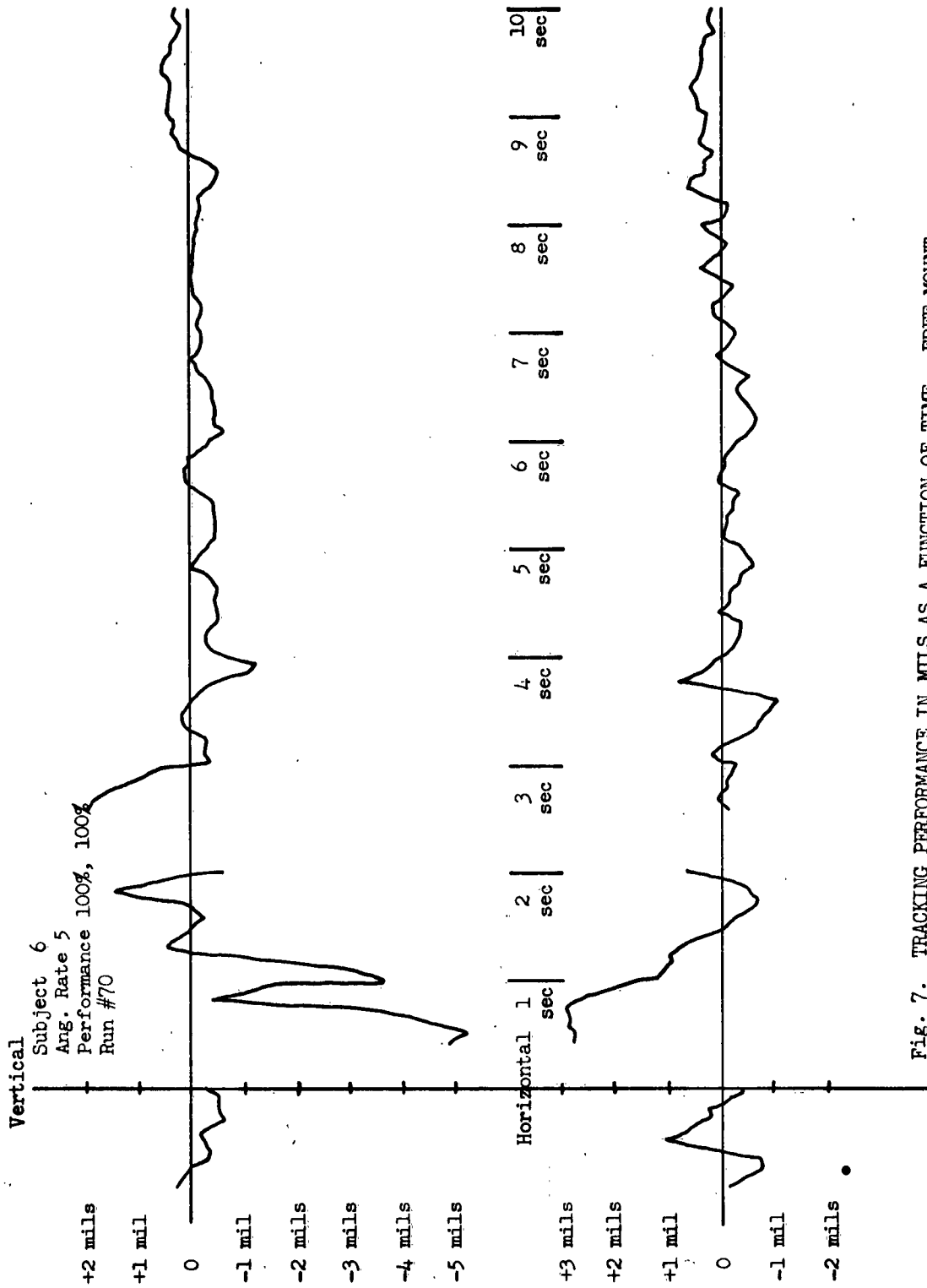
Fig. 7. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – FREE MOUNT

21
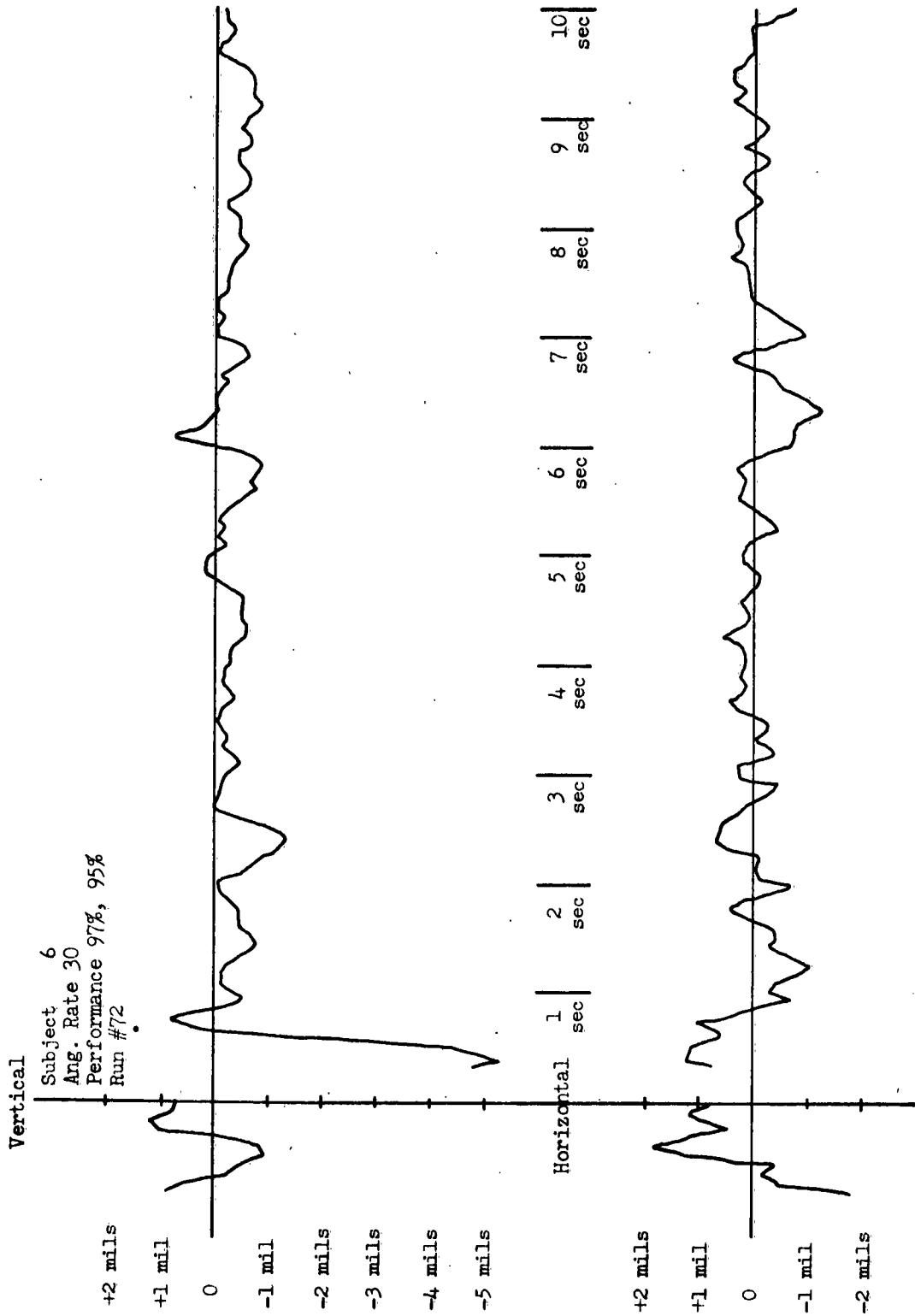
Fig. 8. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME - FREE MOUNT

22
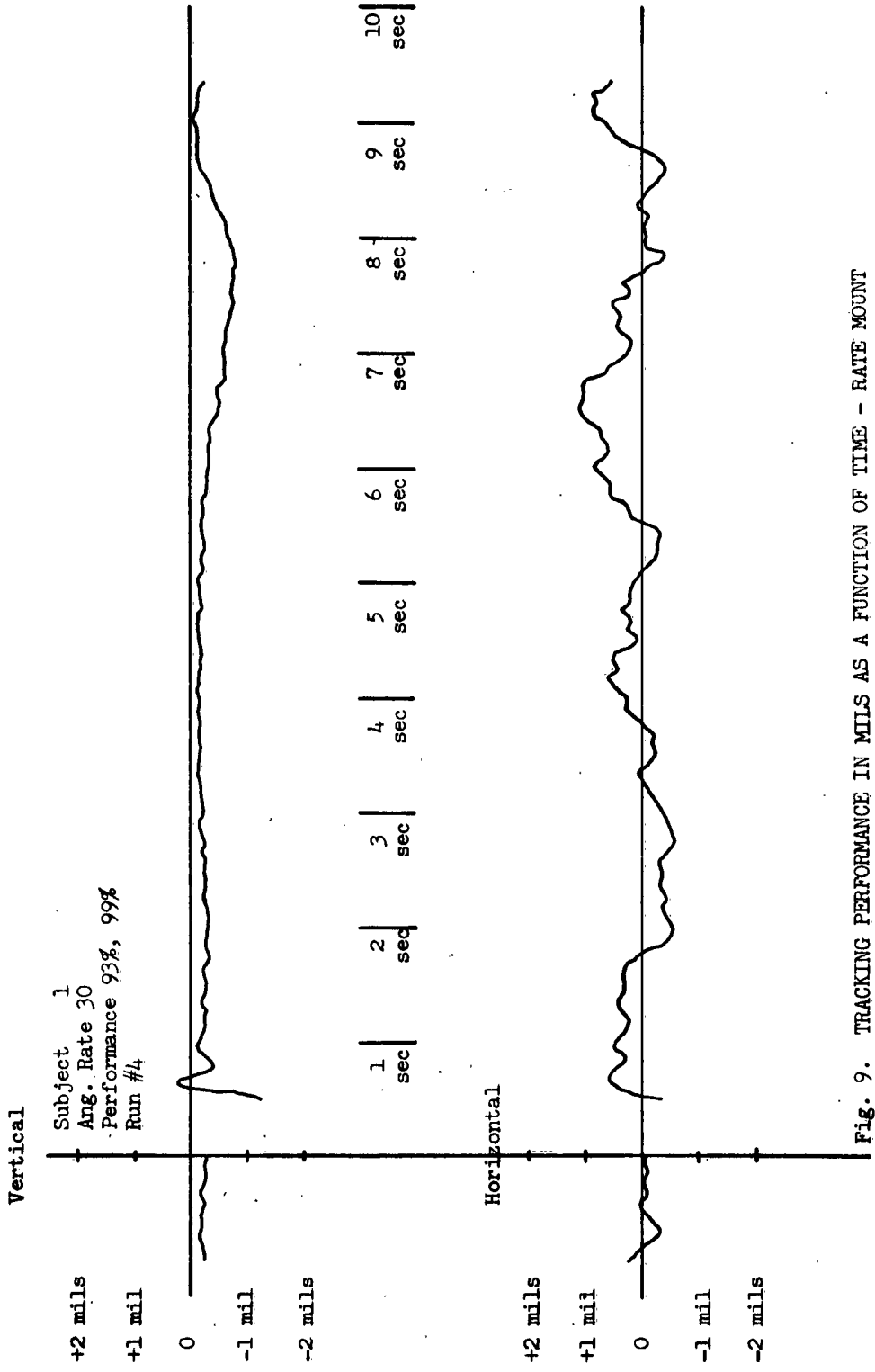
Fig. 9. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME - RATE MOUNT
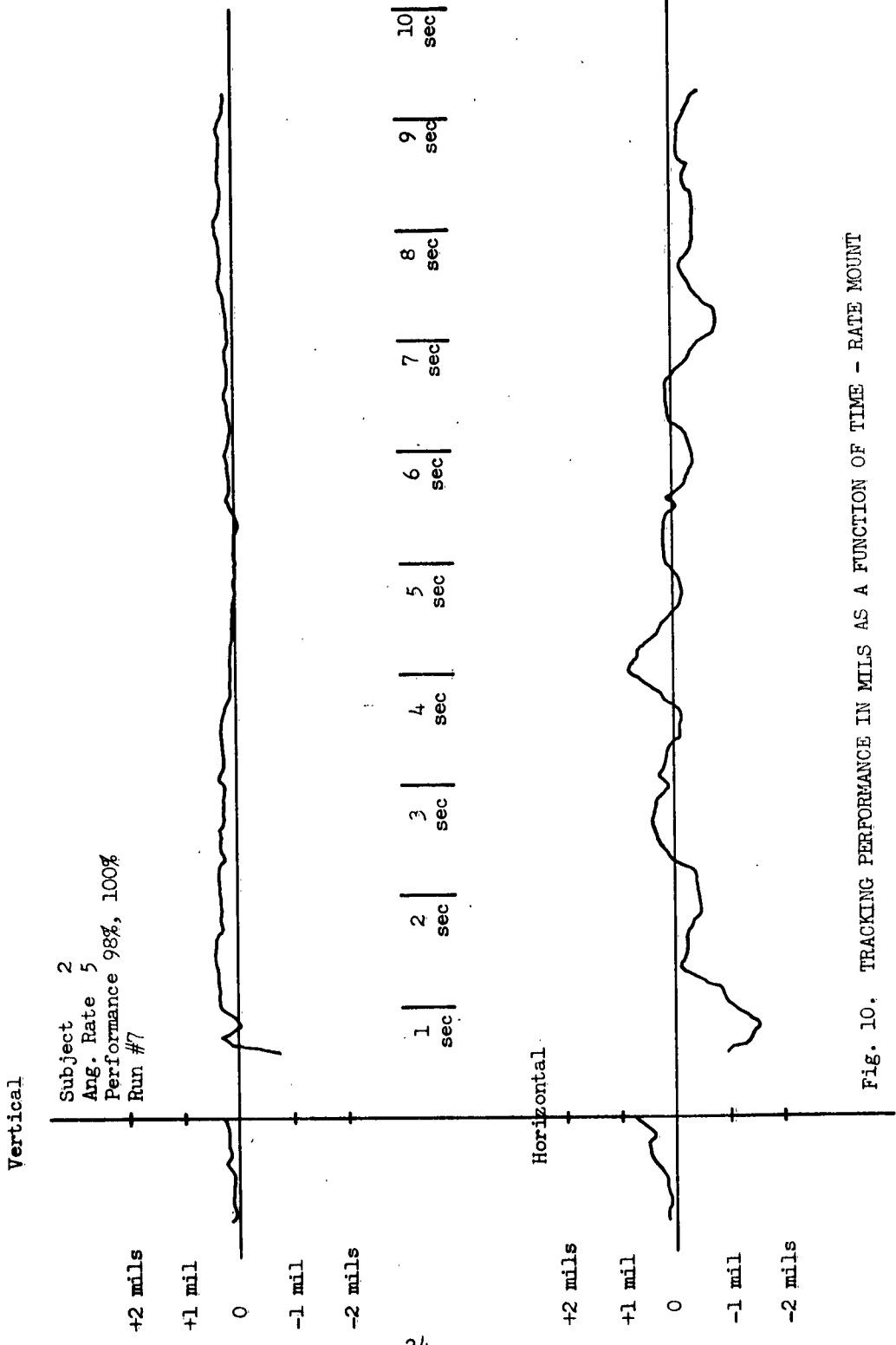
Fig. 10. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – RATE MOUNT

24
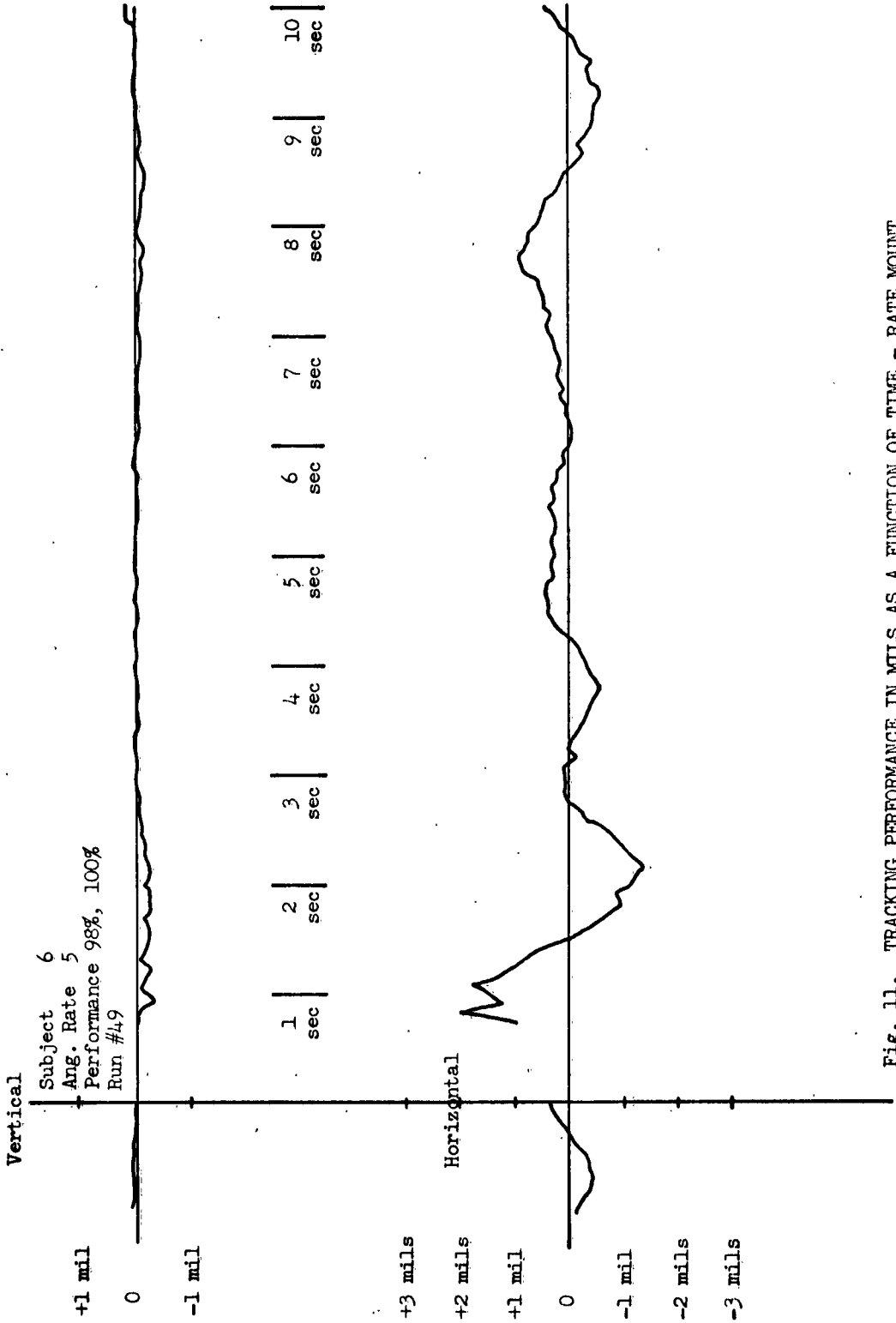
Fig. 11. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME — RATE MOUNT

25
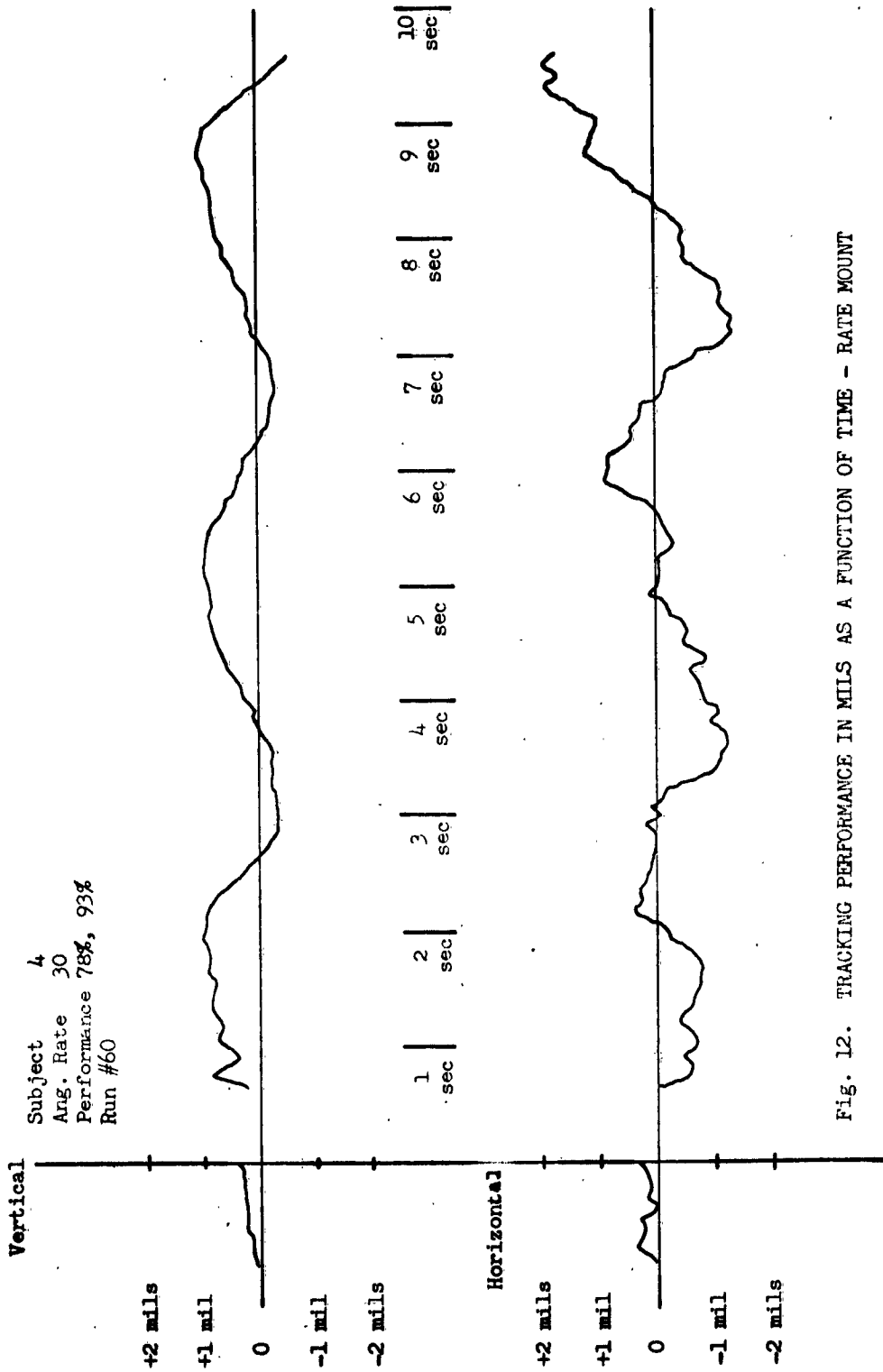
Fig. 12. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – RATE MOUNT
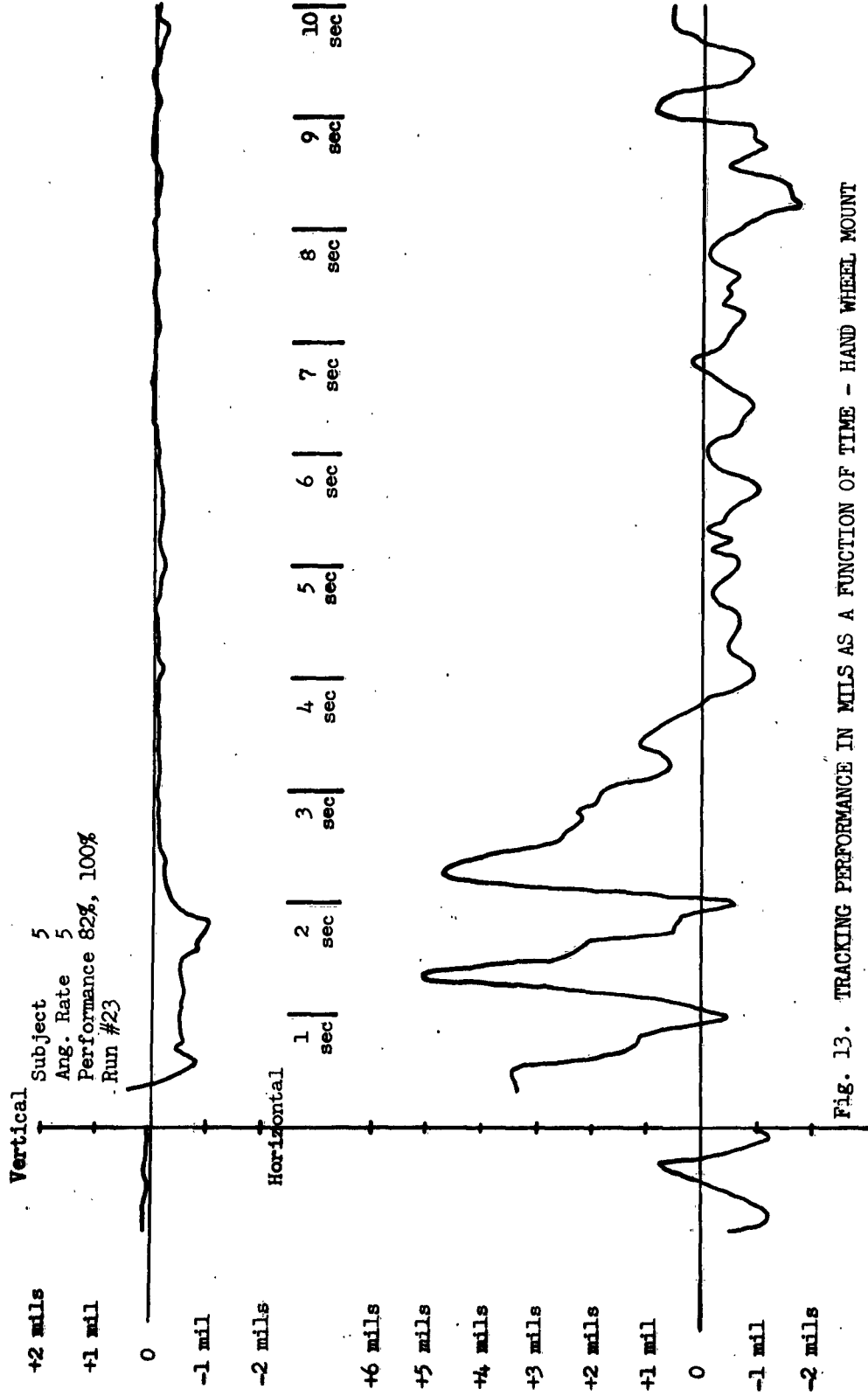
Fig. 13. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – HAND WHEEL MOUNT
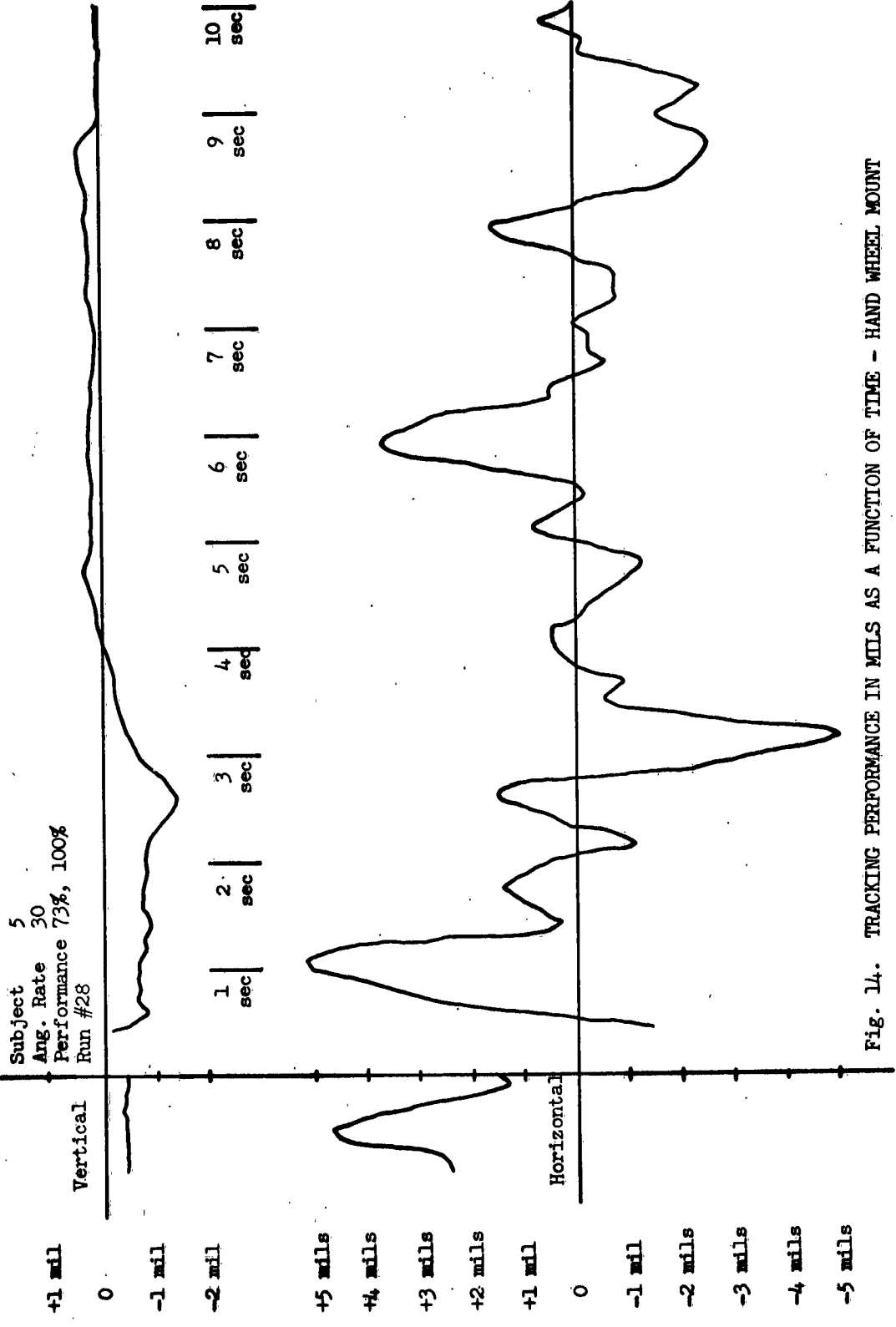
27

Fig. 14. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME – HAND WHEEL MOUNT

Subject 5
Ang. Rate 30
Performance 73%, 100%
Run #28

28
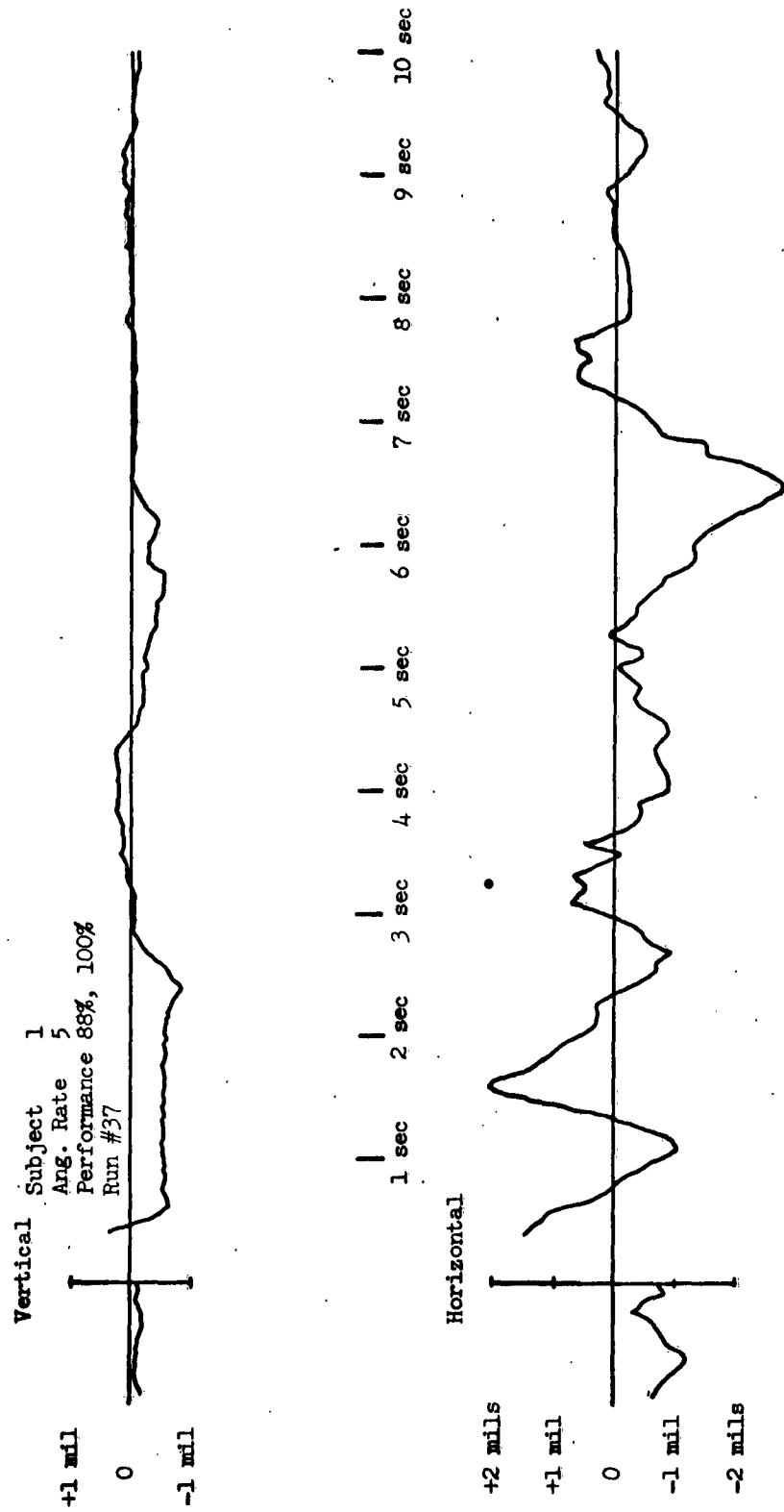
Fig. 15.   TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME — HAND WHEEL MOUNT

29
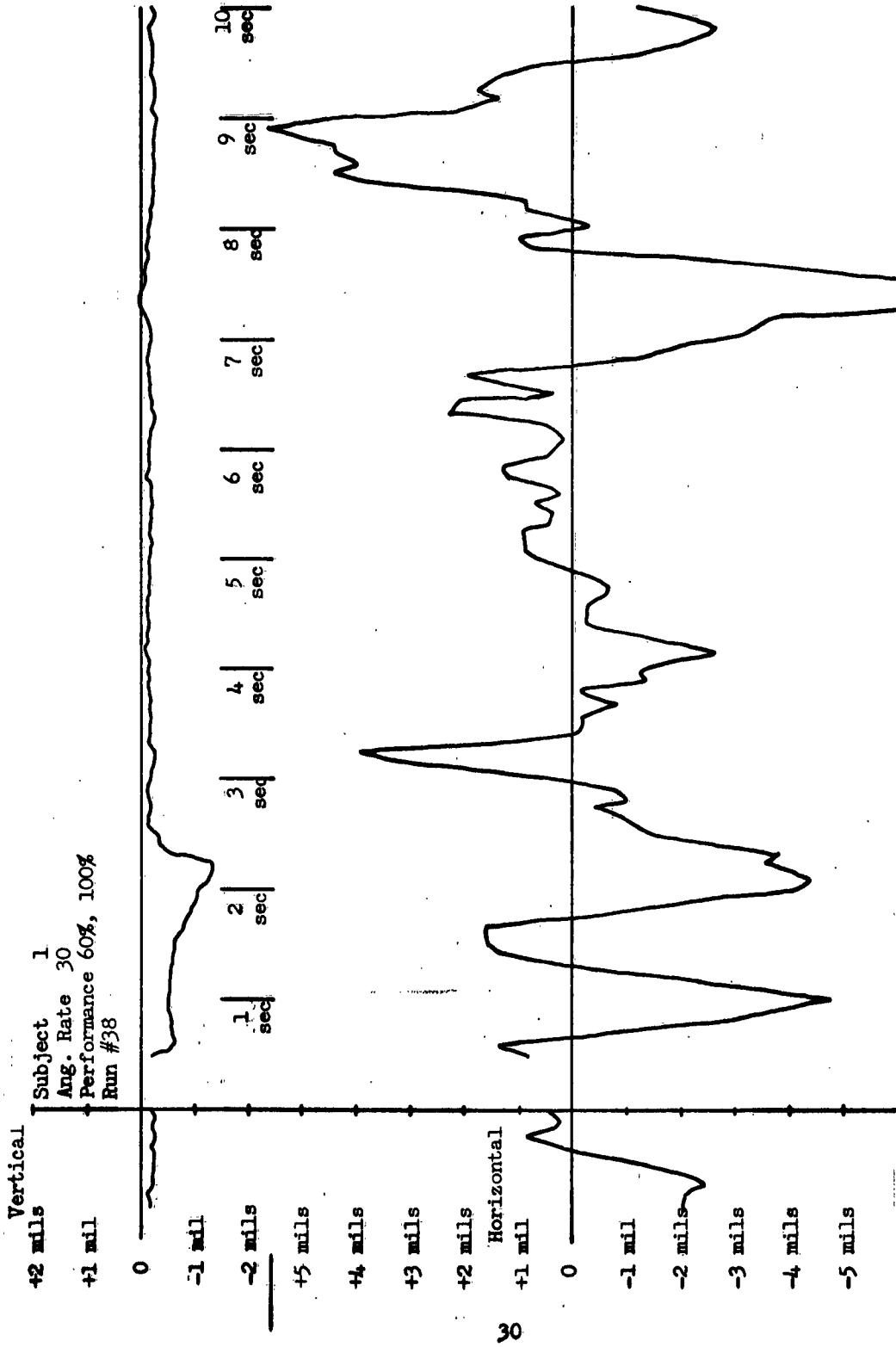
Fig. 16. TRACKING PERFORMANCE IN MILS AS A FUNCTION OF TIME - HAND WHEEL MOUNT

time (seconds)
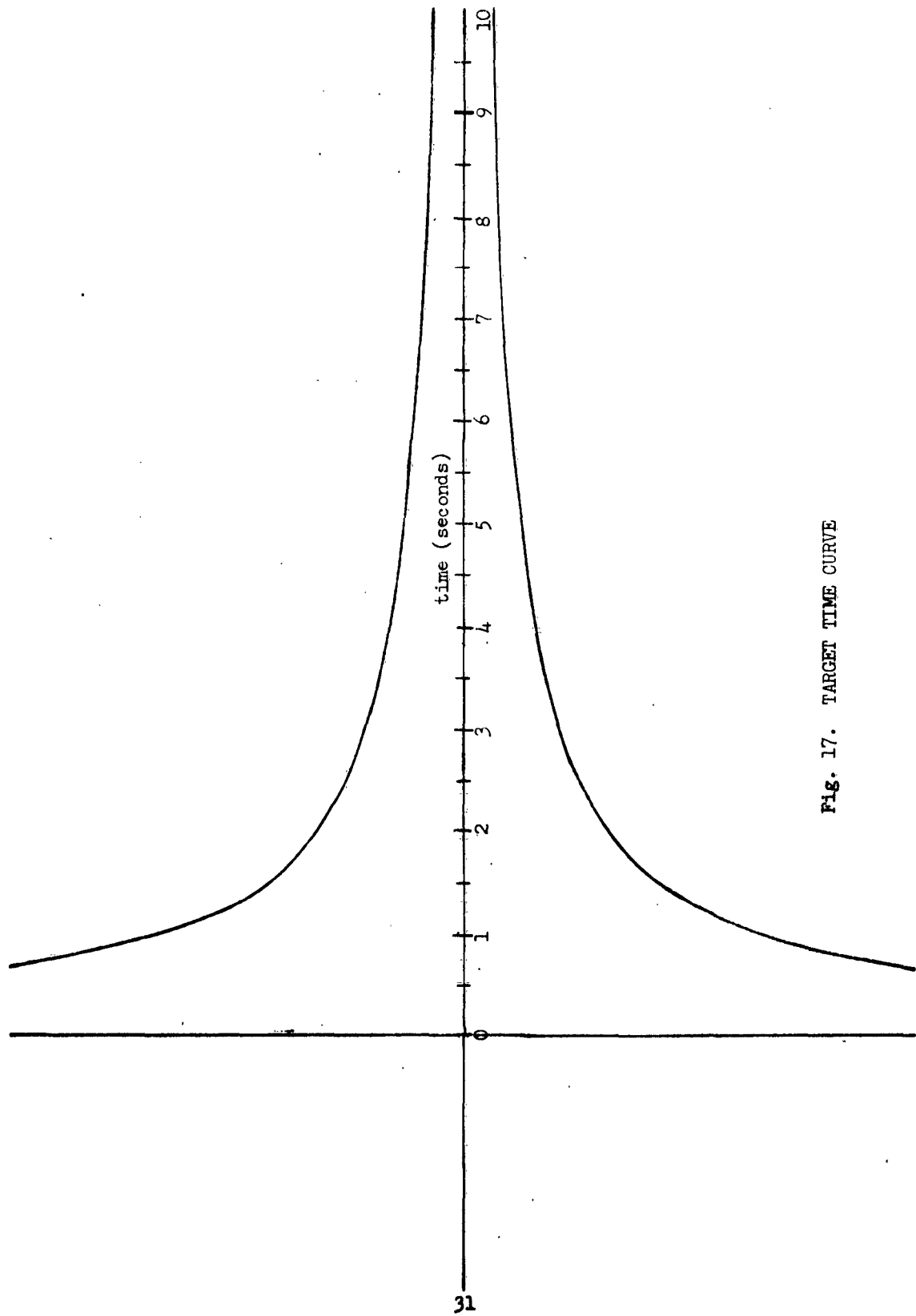
Fig. 17. TARGET TIME CURVE

DISCUSSION

Comparison with Previous Systems

The performance of the rate system compared favorably with the M-48 Tank system performance recorded in the previous study. In both cases an RMS error on the order of one-half mil was achieved without a great deal of practice and without a severe interruption due to the firing environment.

The Free Mount performed surprisingly well for such a basically simple design. The total score was an order of magnitude better than that achieved in previous tests with the XM89 mount, presumably because of weight difference and viscous damping.

The Hand Wheel Mount demonstrated approximately the same performance as previous Hand Wheel Mounts which have been tested. The fact that this system had considerably better mechanical specifications than the other systems but nevertheless had considerable error, leads to the conclusion that a program to improve system performance need not include further investigation of two Hand Wheel Mounts.

Viscous Damping

One of the most important factors in this investigation was the intentional introduction of viscous damping into the operator's tracking mechanism. This has not customarily been done, although it is well known that damping is a necessary factor in other servo loops.

A systematic investigation of optimum damping ratios could not be included in this program, but pilot studies attempted to select suitable ratios on an empirical basis. These studies did demonstrate that damping led to a significant improvement over the no-damping condition.

One theory of how this damping changes the system's characteristics seems quite reasonable. In the case of the Hand Wheel Mount, the low friction and high mechanical advantage created a position

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control system of close to zero load. When tracking a moving target, this system had a high-frequency oscillation known as operator noise. An attempt to damp this by increasing the Hand Wheel inertia decreased the frequency but increased the amplitude, thus acting somewhat like a second-order, or acceleration, system. With the addition of viscous damping, the high-frequency oscillation was reduced because the operator was better able to furnish a constant force than a constantly changing position, thus acting something like a rate system.

In the case of the Free Mount, there was no mechanical advantage, thereby leaving the tube inertia to be overcome. Because human gain varies over a finite range -- and a much smaller range for accurate tracking -- the ability to achieve an optimum damping ratio is dependent on the inertia of the system.* For these reasons, the Free Mount required considerably more damping than the Hand Wheel system. Once again it was found that the high-frequency oscillations were damped because the force requirement effectively established a rate system.

It is interesting to note that the damping was increased once during the test, at the request of gunner number five, for trials #65 through #72. A comparison of the results for the two levels of damping shows smoother tracking and lower RMS error scores with increased damping. This supports the conclusion that viscous damping plays a significant role in the performance of tracking mounts.

Smoothness

The general dynamic characteristics of the tracking error can be seen in Figures 5 through 16. The small oscillations, which appear to be always present, may become important when impressed on a resonant system, and therefore deserve discussion. It is felt that these characteristics can be modified and controlled.

The oscillations in the Free Mount at about 3 cps are attributed to mechanical compliance in the mount, as this was found to be its resonant frequency. Careful attention to rigid design and optimal damping should reduce or eliminate this problem.

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*The damping ratio = $\dfrac{D}{\sqrt{2JK}}$ where D is viscous damping, J is inertia, and K is gain probably applies.

The oscillations in the Rate Mount were of a higher frequency than found previously with the M-48 Tank system. This may have been due to the higher acceleration of the Rate Mount. In any case, the inclusion of electro-mechanical servos allows considerable freedom in manipulating transfer functions, and a carefully selected transfer characteristic should be able to modify system output to achieve the desired results.

Mechanical Reduction

Since both the Hand Wheel Mount and Free Mount were viscously-damped, position-control systems, the difference in performance must be attributed to the difference in mechanical reduction (200:1 versus 1:1) or to the manner in which azimuth and elevation control were integrated. It would be possible to use a low reduction (2:1 to 10:1) with an integrated position control and perhaps achieve greater accuracy if the requirements for other important variables (damping, friction, backlash, and compliance) are met. This possibility would require study, however, to assure that the benefits justify the complexity.

SUMMARY AND RECOMMENDATIONS

1. Both a lightweight rate system and a viscously damped Free Mount can achieve 0.5 mils RMS error when used by gunners with very little training.

2. A Hand Wheel Mount cannot achieve the same accuracy when used under the same conditions.

3. Future research should be conducted in the following areas:

a. Define the optimum damping ratio and the limit of inertia for Free Mount systems.

b. Investigate the ability to control oscillations by adjusting damping in the Free Mount and the transfer function in the rate mount.

c. Determine the minimum necessary rate for the servo drive. If it is found that 0.1 mils per second is lower than needed, the design of the system could be simplified or a higher maximum rate incorporated.

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Viscous Damping

One of the most important factors in this investigation was the intentional introduction of viscous damping into the operator's tracking mechanism. This has not customarily been done, although it is well known that damping is a necessary factor in other servo loops.

A systematic investigation of optimum damping ratios could not be included in this program, but pilot studies attempted to select suitable ratios on an empirical basis. These studies did demonstrate that damping led to a significant improvement over the no-damping condition.

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33

control system of close to zero load. When tracking a moving target, this system had a high-frequency oscillation known as operator noise. An attempt to damp this by increasing the Hand Wheel inertia decreased the frequency but increased the amplitude, thus acting somewhat like a second-order, or acceleration, system. With the addition of viscous damping, the high-frequency oscillation was reduced because the operator was better able to furnish a constant force than a constantly changing position, thus acting something like a rate system.

In the case of the Free Mount, there was no mechanical advantage, thereby leaving the tube inertia to be overcome. Because human gain varies over a finite range -- and a much smaller range for accurate tracking -- the ability to achieve an optimum damping ratio is dependent on the inertia of the system.* For these reasons, the Free Mount required considerably more damping than the Hand Wheel system. Once again it was found that the high-frequency oscillations were damped because the force requirement effectively established a rate system.

It is interesting to note that the damping was increased once during the test, at the request of gunner number five, for trials #65 through #72. A comparison of the results for the two levels of damping shows smoother tracking and lower RMS error scores with increased damping. This supports the conclusion that viscous damping plays a significant role in the performance of tracking mounts.

Smoothness

The general dynamic characteristics of the tracking error can be seen in Figures 5 through 16. The small oscillations, which appear to be always present, may become important when impressed on a resonant system, and therefore deserve discussion. It is felt that these characteristics can be modified and controlled.

The oscillations in the Free Mount at about 3 cps are attributed to mechanical compliance in the mount, as this was found to be its resonant frequency. Careful attention to rigid design and optimal damping should reduce or eliminate this problem.

---

*The damping ratio $= \dfrac{D}{\sqrt{2JK}}$ where D is viscous damping, J is inertia, and K is gain probably applies.

The oscillations in the Rate Mount were of a higher frequency than found previously with the M-48 Tank system. This may have been due to the higher acceleration of the Rate Mount. In any case, the inclusion of electro-mechanical servos allows considerable freedom in manipulating transfer functions, and a carefully selected transfer characteristic should be able to modify system output to achieve the desired results.

Mechanical Reduction

Since both the Hand Wheel Mount and Free Mount were viscously-damped, position-control systems, the difference in performance must be attributed to the difference in mechanical reduction (200:1 versus 1:1) or to the manner in which azimuth and elevation control were integrated. It would be possible to use a low reduction (2:1 to 10:1) with an integrated position control and perhaps achieve greater accuracy if the requirements for other important variables (damping, friction, backlash, and compliance) are met. This possibility would require study, however, to assure that the benefits justify the complexity.

SUMMARY AND RECOMMENDATIONS

1. Both a lightweight rate system and a viscously damped Free Mount can achieve 0.5 mils RMS error when used by gunners with very little training.

2. A Hand Wheel Mount cannot achieve the same accuracy when used under the same conditions.

3. Future research should be conducted in the following areas:

a. Define the optimum damping ratio and the limit of inertia for Free Mount systems.

b. Investigate the ability to control oscillations by adjusting damping in the Free Mount and the transfer function in the rate mount.

c. Determine the minimum necessary rate for the servo drive. If it is found that 0.1 mils per second is lower than needed, the design of the system could be simplified or a higher maximum rate incorporated.

Labels on image: CAMERA, SAGINAW BALL SCREW DRIVE, ELEV. , HARMONIC DRIVE, FIRING SWITCH

APPENDIX A

The attention throughout this design and construction period was to fabricate mounts with as nearly "perfect" operating characteristics as possible. Secondly, the mounts were intended to be reasonable facsimiles of field mounts, rather than laboratory fixtures.

Due to time and facility limitations, many compromises were made sometimes affecting performance of the mounts, but mostly compromising only esthetic appeal.

This discussion will point out the distinguishing features of each of the mounts, together with the design objectives and the achieved operating characteristics.

Hand Wheel Mounts

The basic difficulties with all the hand wheel mounts previously investigated appeared to be excessive coulomb friction in the hand wheel drives; excessive cogging and backlash; roughness of the gear reductions, and excessive compliance in the elevation suspension. The first three deficiencies may be overcome by using a Harmonic Drive, which is a unique device patented by the United Shoe Machinery Company. However, in order to make the system rigid, a ball screw could be more suitable for elevating a mechanism. Both drives can offer all the fine qualities desired for this hand wheel drive. The accompanying table lists the measured characteristics. It should be noted that the azimuth drive was not backlash-free during the firing program, although it was (to less than 0.1 mils) immediately after assembly. The unit obtained had not been designed for minimum backlash, but it is certainly feasible to meet the backlash requirements with such a device. Even the backlash observed was a great improvement over existing mounts. However, due to the low azimuth bearing friction, its effect was more marked. That is, the slight perturbations applied to the mount by the gunner in the course of tracking were sufficient to cause the mount to jitter. Other gun mounts, having stiffer azimuth bearings, were not as susceptible to this defect.

The elevation drive, using the ball-bearing screw, was essentially friction- and backlash-free. The gun tube and instrumentation mounted on the cradle were balanced in such a way that there was a slight loading on the screw -- not enough to be noticeable when elevating the tube, but enough to eliminate any backlash.
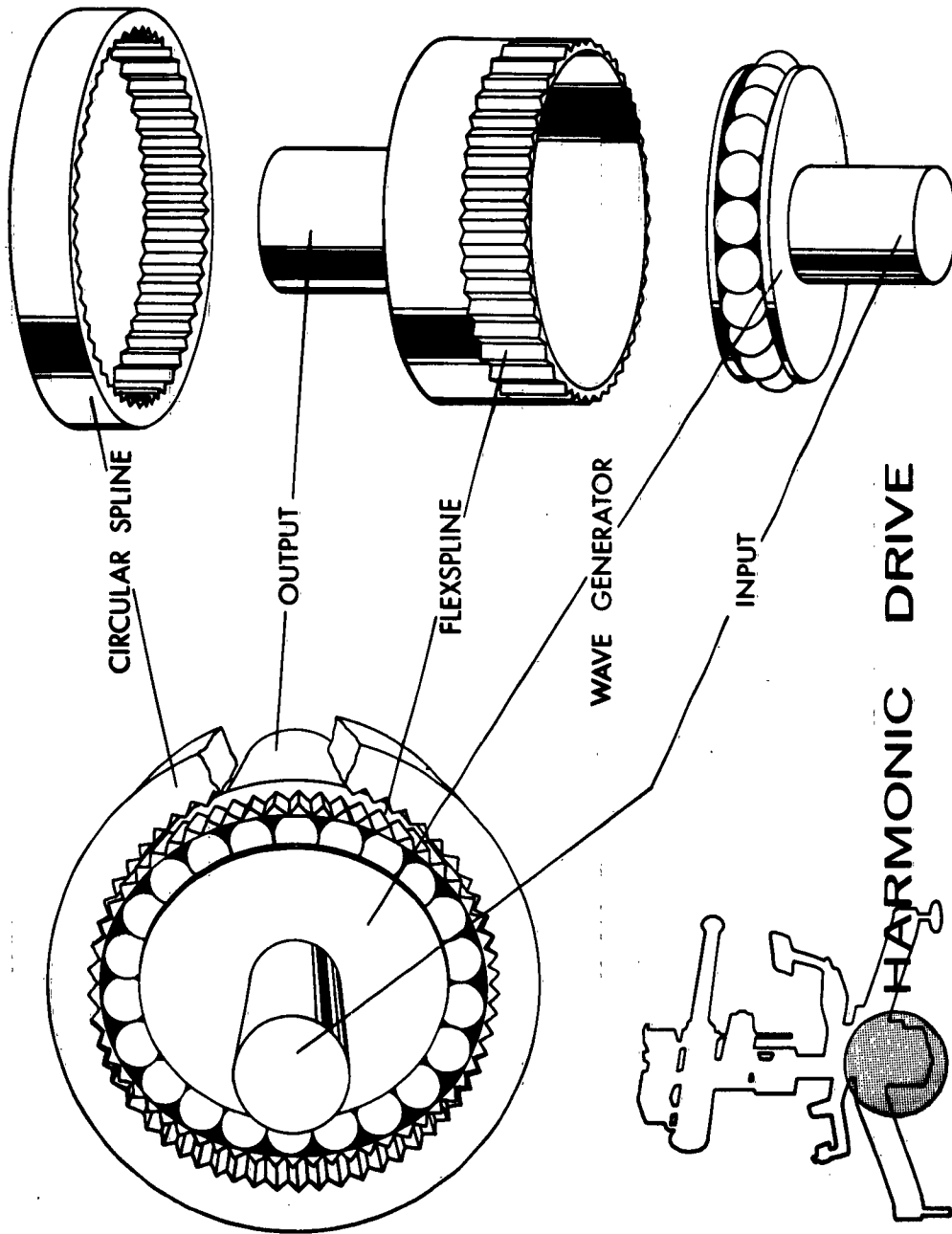
CIRCULAR SPLINE

OUTPUT

FLEXSPLINE

WAVE GENERATOR

INPUT

HARMONIC DRIVE

Fig. 1. HARMONIC DRIVE

TABLE 1

Properties of Hand Wheel Mounts
(Azimuth only)

	Backlash	Gear Ratio (Approx.)	Starting		Moving	
			Force	Torque	Force	Torque
XM-29	2 mils	400:1	3.5 lb.	13 in-lb.	3 lb.	11 in-lb.
M-20	2 mils	140:1	4 lb.	12 in-lb.	4.5 lb.	13.5 in-lb.
M-112	2 mils	170:1	.75 lb.	2.1 in-lb.	.25 lb.	.7 in-lb.
HEL	.6 mil	175:1	.1 lb.	.3	.3 lbs/mils/sec	1 in-lb/mils/sec

– – – – – Properties of Rate Mount (HEL) – – – – –

	Azimuth	Elevation
Maximum rate	100 mils/sec	15 mils/sec
Minimum rate	.1 mils/sec	.1 mils/sec
Backlash	.1 mils	.1 mils
Amplifier gain	10 amps/volt	See text.
Amplifier frequency response (-3dB)	1 kc	1 kc

– – – – – Properties of Free Mount (HEL) – – – – –

Compliance	.47 mils/lb-ft
Damping	.24 lb-ft/mil/sec
Friction	1.6 lb-ft
Movement of Inertia	1.92 slug-ft^2 (calculated, without round)

RATE MOUNT

8X ELBOW SIGHT WITH CROSSHAIR RETICLE

ELEV. MOTOR & GEAR REDUCER

CONTROL HANDLE WITH SLEW THUMBSWITCH & FIRING TRIGER

AZ. & ELEV. CONTROL PICK OFFS & AMPLIFIERS

AZIMUTH TACHOMETER, MOTORS AND FIRST GEARHEAD

HARMONIC DRIVE
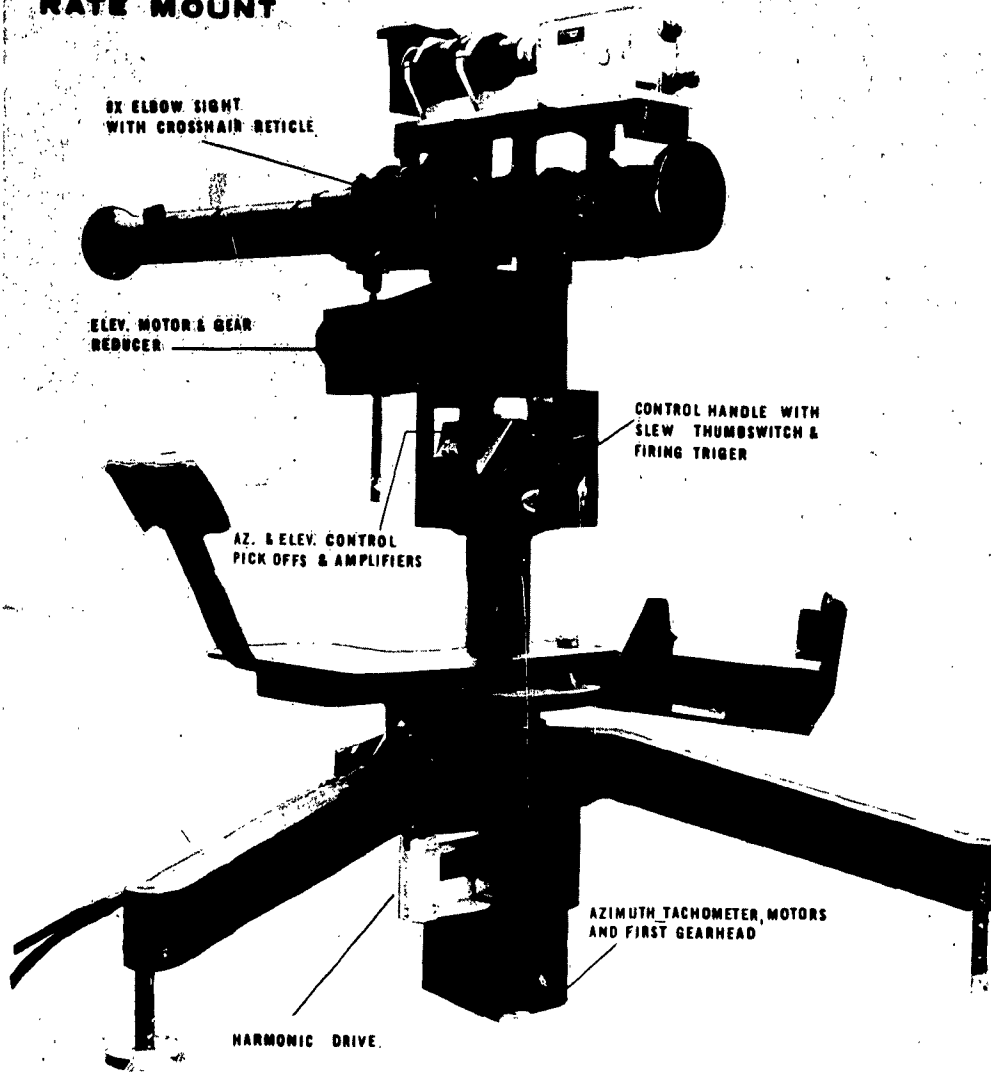
PLATE 3

Rate Mount

Assuming one has an essentially friction- and backlash-free Hand Wheel Mount it remains only to provide a suitable motor drive to power the equivalent of the hand wheels. The requirements for the azimuth drive were determined by the fact that, for the most part, one would not expect to find a target moving faster than 30 mils/sec, which corresponds roughly to a target in a cross-over trajectory of 500 meters with a velocity of 30 miles/hr. The minimum tracking rate is determined primarily by the ability of the operator to discern small changes in small rates and it was felt, as a first guess, that a rate of .1 mils/sec would be appropriate. As it turned out, with the linear transfer function of the control that was used, a change of .1 mil/sec is a slight movement that most operators seldom achieve. It is believed, without experimental backing, that perhaps .2 mil/sec would be a more suitable low rate. A maximum slewing rate of 100 mils/sec was achieved, and this rate seems adequate for the task at hand. Assuming that targets normally encountered would not be climbing or descending slopes much greater than 10%, the maximum elevation rate was set at 10 mils/sec. Although this rate is adequate for tracking, it became apparent that rates of 60 to 100 mils/sec would be needed for target acquisition.

Without resorting to a two-speed transmission to obtain the high and low rates, this means that the azimuth motor must be capable of a 1000:1 speed range. Allowing for a top motor speed in the order of 4000 to 8000 rpm, this means that the minimum speed must be on the order of 4 to 8 rpm, which is rather low for conventional DC motors. A digital or AC system would appear feasible; however, the circuitry becomes much more complex. The Printed Circuit Motor, which is an unconventional DC motor, appeared promising due to the lack of any cogging and the large number of commutator segments. The considerations for the elevation drive were similar, except that the required speed range was only 100:1. The maximum motor speeds were set at 5000 rpm, which therefore led to the minimum speeds of 5 and 50 rpm.

There were two reasons for using feedback control of the motor drives: (1) it would have been impossible to obtain the wide speed range (1000:1) in the azimuth drive without resorting to the use of feedback, and (2) it would have been just as difficult to design a simple voltage control that would have met the power requirements and yet would have satisfied the mechanical requirements of compactness and smoothness of operation. Block diagrams of the two motor control systems are shown in Figures 2 and 3. The circuitry was quite straightforward, employing a silicon differential input stage to minimize the drift problems which normally beset this type of servo. The drift problem is not as severe as it might be in this case, since a dead zone -- which is desirable from a human engineering standpoint -- was achieved by driving the amplifier below cutoff. The transfer function of the controls approximated a

Note: Motor and
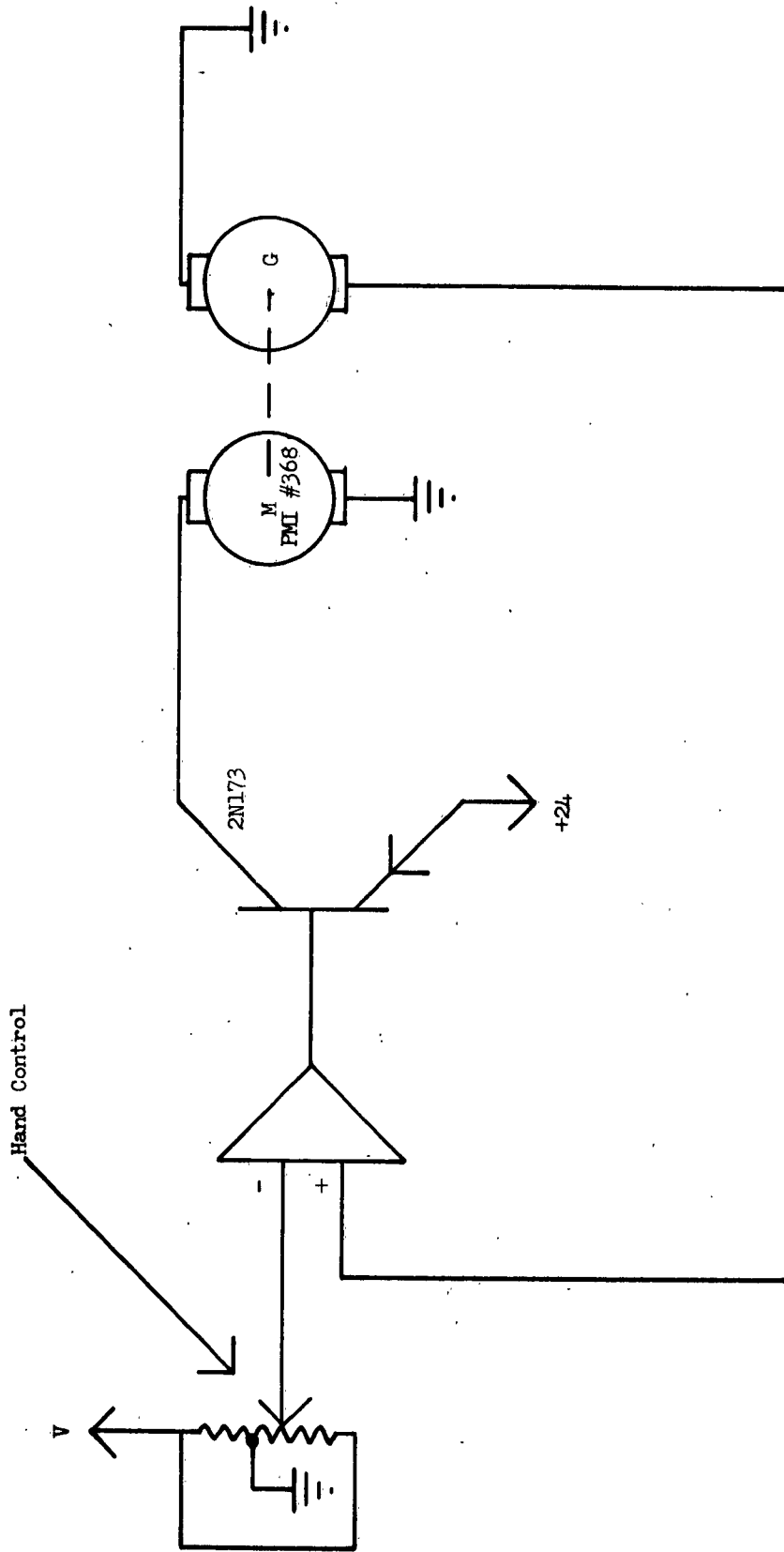Tachometer reversed
by means of a relay.

Hand Control

2N173

M
PMI #368

G

+24

V

Fig. 2. AZIMUTH RATE DRIVE

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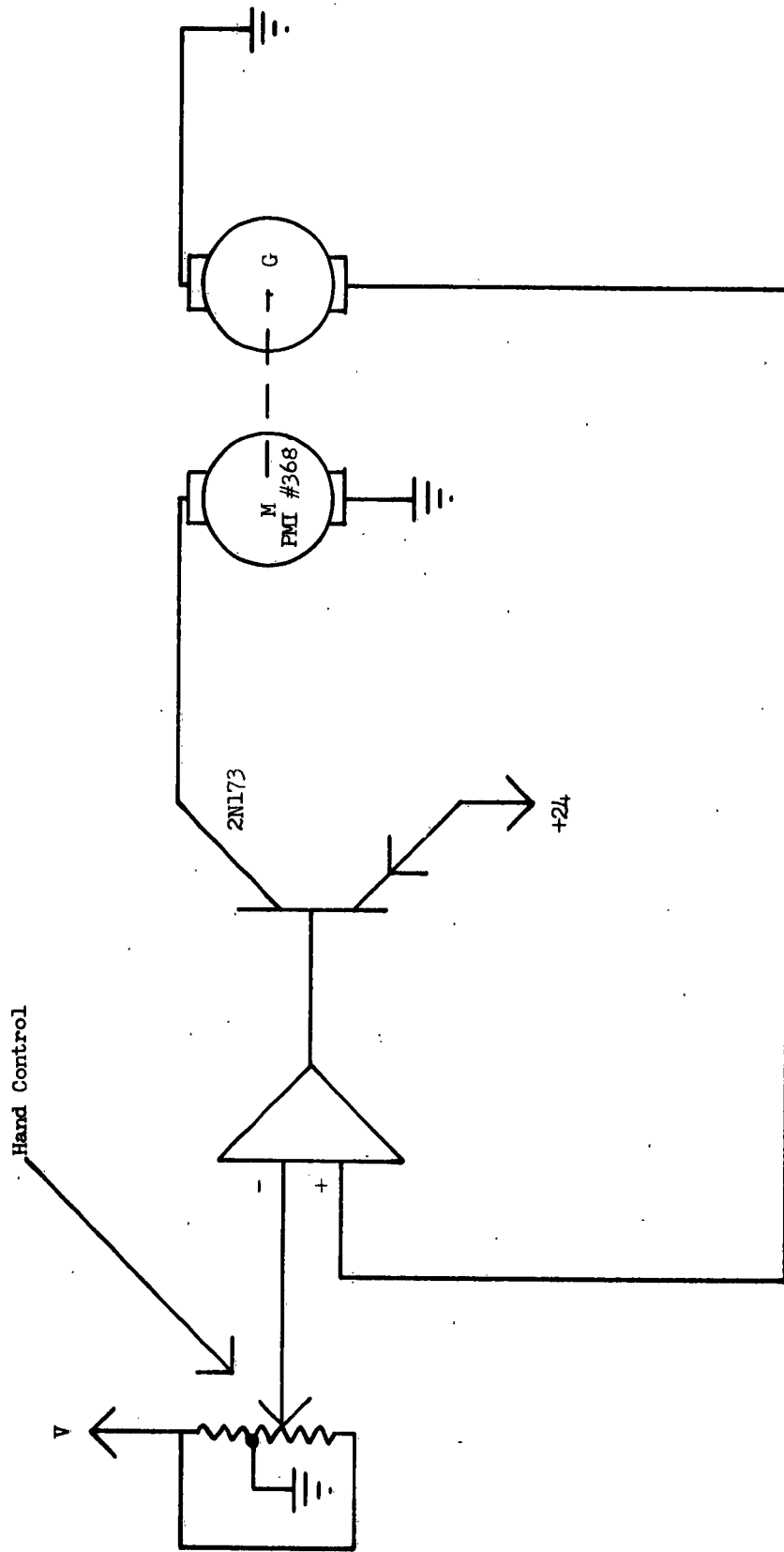Fig. 2. AZIMUTH RATE DRIVE

Note: Motor and
Tachometer reversed
by means of a relay.

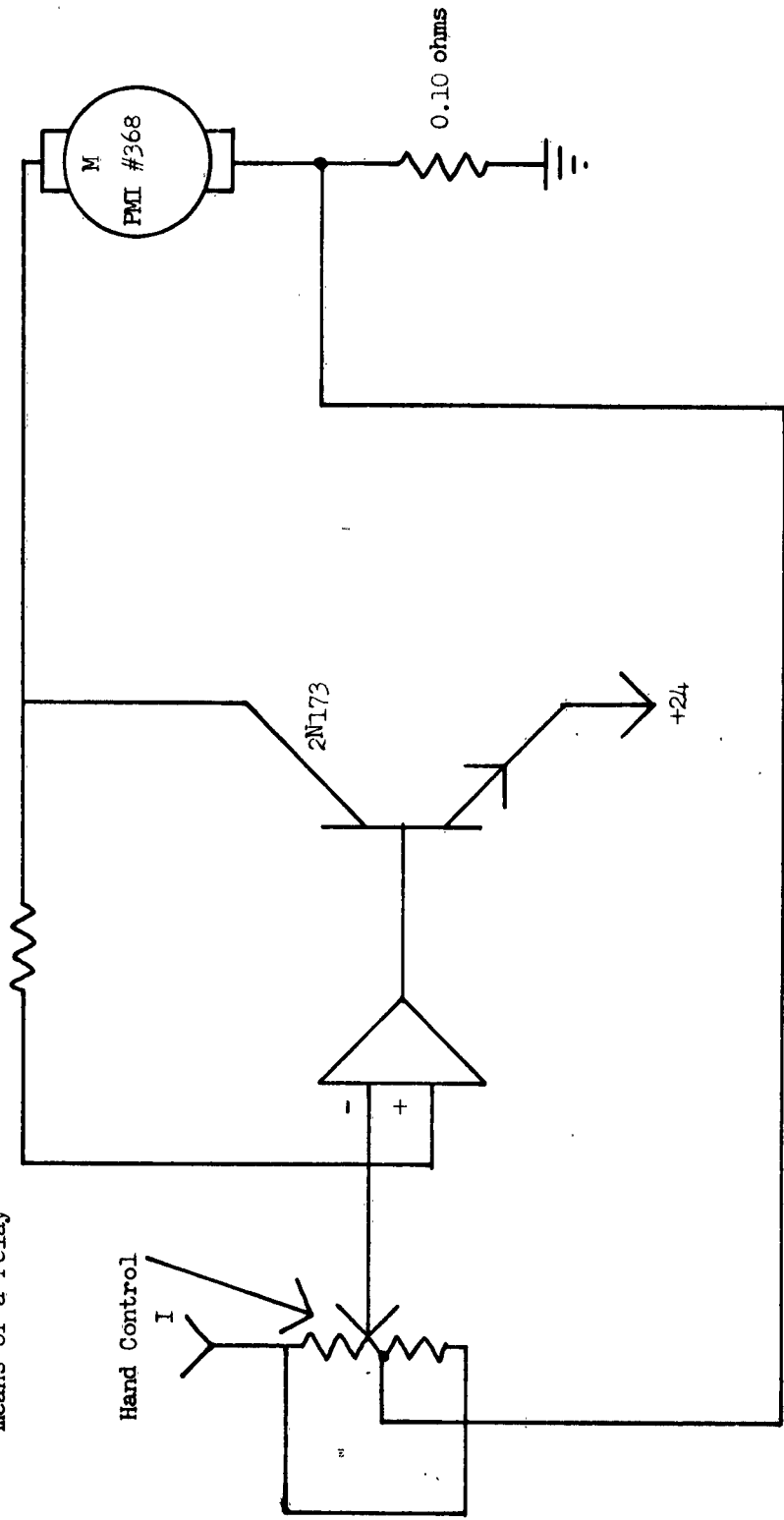Note: Motor reversed by
means of a relay

Fig. 3. ELEVATION RATE DRIVE

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straight line with a dead zone of about 5% of the operating range. The azimuth drive system consisted of a simple rate servo with tachometer feedback, using a Printed Motors, Inc. #368 motor and a tachometer of unknown vintage. The amplifier had a gain of 10 amperes per volt, and frequency response 3 dB down at about 1.0 kc. Since the output stage was single-ended, one-way-only damping was inherent in its construction, although the motor had inherent damping of about 2 oz-in/k RPM.

The elevation amplifier was roughly the same as the azimuth amplifier. However, instead of taking negative feedback from the tachometer, positive feedback was taken from the motor through a sampling resistor in the armature circuit, while negative feedback was used to stabilize the open loop gain at a value slightly less than:

$$A = \frac{Z_m \, K_E}{R_s \, K_I} = 5.67$$

where Z_m = mechanical impedance = 85×10^{-3} KRPM/oz-in

R_s = sampling resistance = 0.1 ohms

K_E = Back EMF/kRPM = 2.22 volts kRPM

K_I = amperes/unit torque = .33 amp/oz-in

The lowest revolution rate for this system was around 50 RPM, due primarily to brush noise considerations and one-way damping. It is felt that more careful design might reduce this figure significantly.

The power requirement for both drives was about 30 watts per coordinate at tracking rates from 5 to 30 mil/sec.

There is no accurate estimate of output-torque requirements for steady state tracking with this type of mount. Because dynamic loads cause the most severe problem, it was assumed that a gunner shifting position would introduce the peak torques. A pilot study indicated these loads would be less than 10 lb-ft. On the completed mount, loads of 20 lb-ft had negligible effects on the rate. For small changes in rate, a response time of about .1 sec or faster will suffice. The design objective was an acceleration of 100 mils/sec^2. However, if it is demonstrated that a rate-aided system is necessary, then the torque requirements might become a bit more stringent, although customary practice is to simply forget about the rate aiding for large rate changes -- that is, fix the angular acceleration at some value which will tend to wash out the rate aiding for large step inputs.

Free Mount

The portions of the program described in Human Engineering Laboratories Technical Note 6-62, gave insight into the manner in which the combination of gunner plus XM89 mount behaves. The mount is a "free" mount, in that it is positioned in much the same way that one would aim a tripod-mounted movie camera. At that time the system mounted a 106mm recoilless tube, weighing about 250 lbs, and about 11 feet long. It thus represents a large amount of inertia. In addition, bearing friction was relatively high -- the starting torque required was in excess of ten pound-feet. A qualitative analogy between a feedback control system and the mount-gunner combination suggests that, since this is the equivalent of a second-order system, the most appropriate improvements would be reducing inertia and coulomb friction and adding viscous damping, rather than modifying the gunner. Fortunately, the 3.5" tube would be considerably lighter than the 106mm recoilless tube, and, by replacing the ball-and-socket employed on the XM89 with a gimbal, friction could also be reduced. The design of the viscous dampers will be discussed below. One point should be brought out here: it is important to reduce coulomb friction, even though one must then add viscous friction. Consider the graph of Figure 4, where the solid line represents a frictionless system, and the dashed line a "non-ideal" system. The variations in force that a noisy input (gunner) would impress on the system in attempting to maintain a certain rate will lead to different velocity variations in the two cases. In addition, when the noisy actuator is part of a feedback system with an appreciable lag component, it would appear that the noisiness of the actuator would actually be increased.

The dampers were constructed as shown in Figure 5. Adjustments were made by releasing the outer edges of the stators so they could revolve. Releasing all seven stators reduces the damping by 50%. Releasing the rotors instead of the stators would have allowed a much wider range of damping, but at the expense of more complications in the mechanism. The fluid used was Dow Corning's 200 fluid, 2.5×10^6 cs nominal viscosity. The design of this damper assumed a constant velocity gradient between stator and rotor. Experiments have shown that this is a valid assumption for the range of spacings usually encountered, since design and measurements correspond within
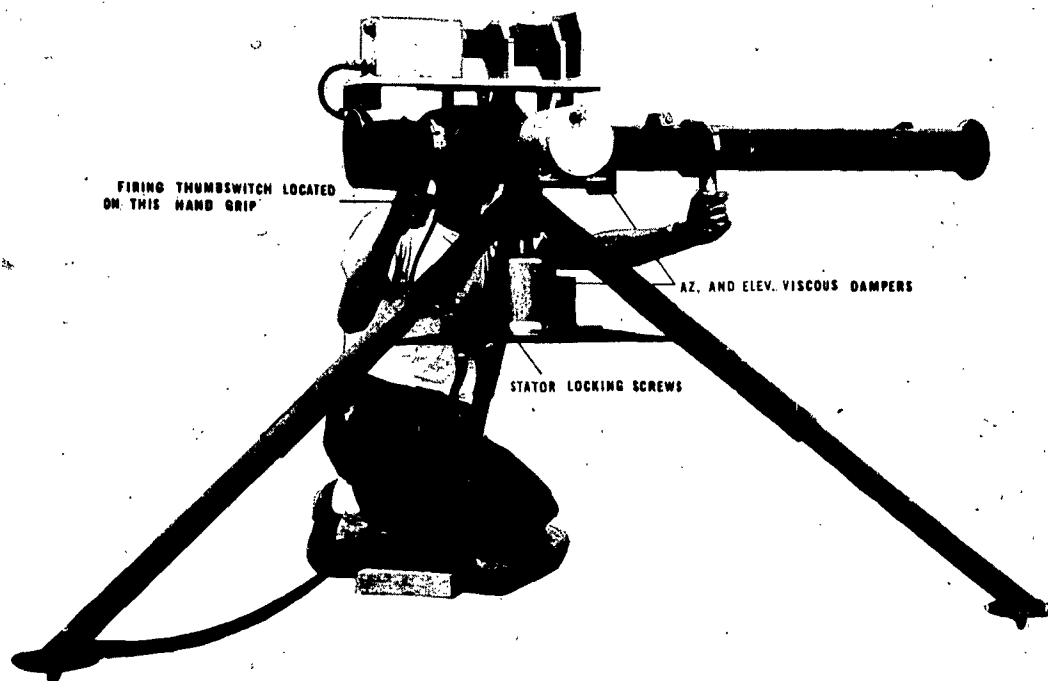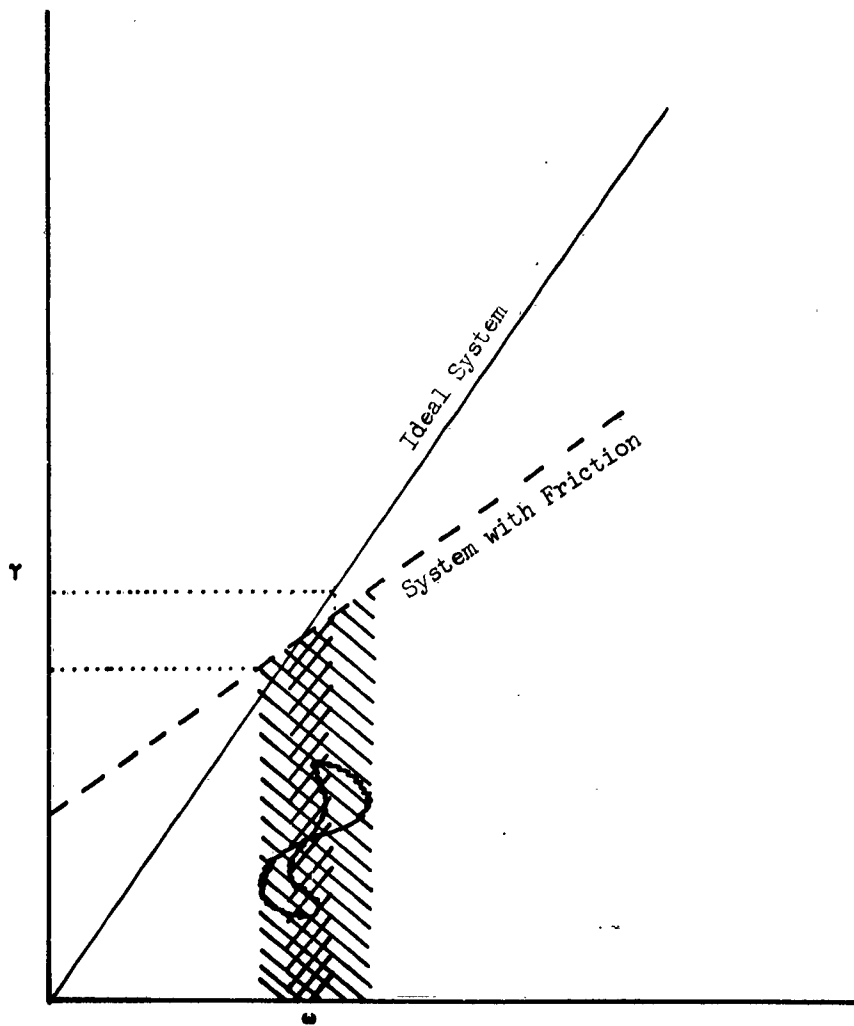
FREE MOUNT

FIRING THUMBSWITCH LOCATED
ON THIS HAND GRIP

AZ, AND ELEV. VISCOUS DAMPERS

STATOR LOCKING SCREWS

PLATE 2

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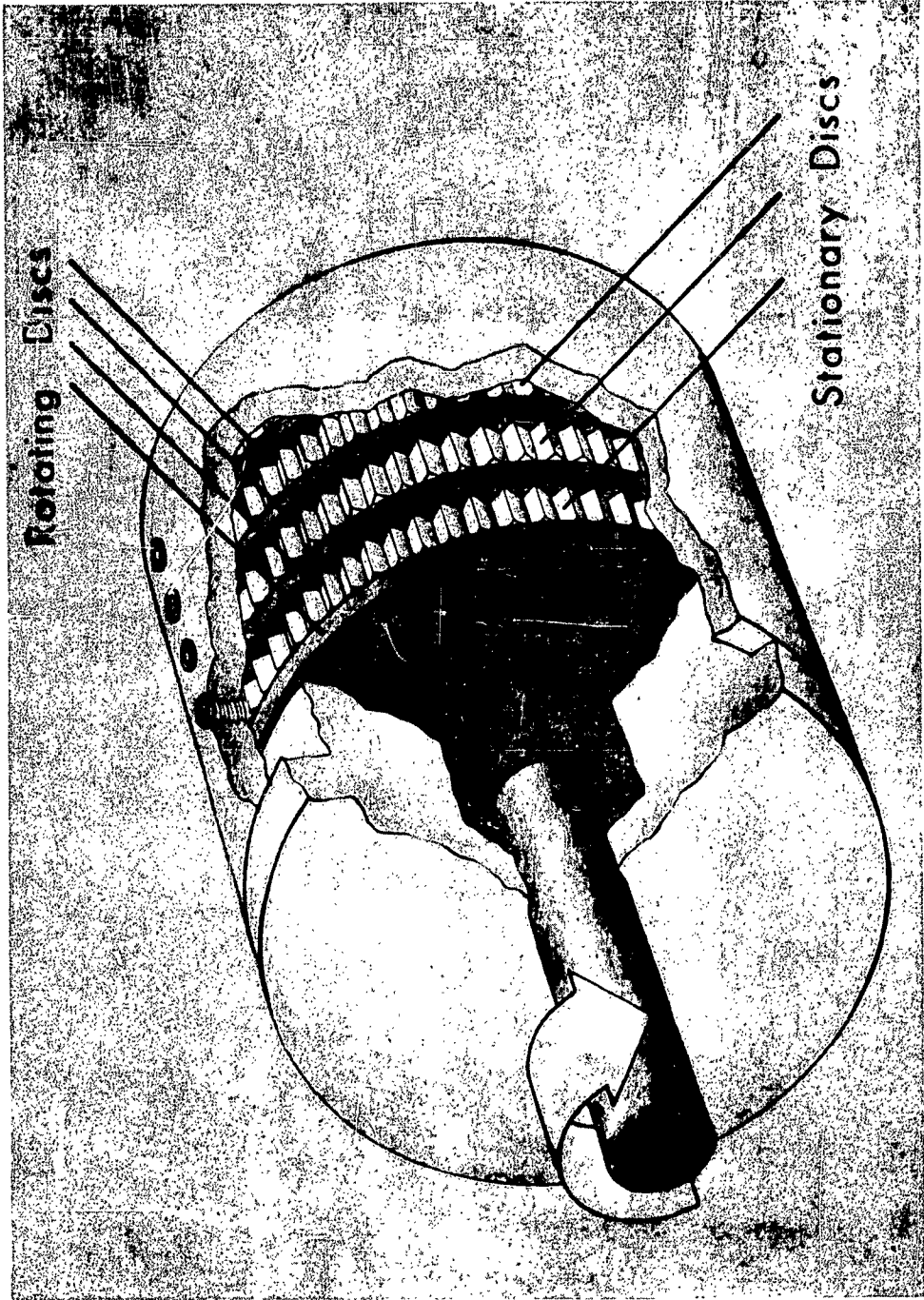**Fig. 4. NOISE CHARACTERISTICS OF REAL SYSTEMS**

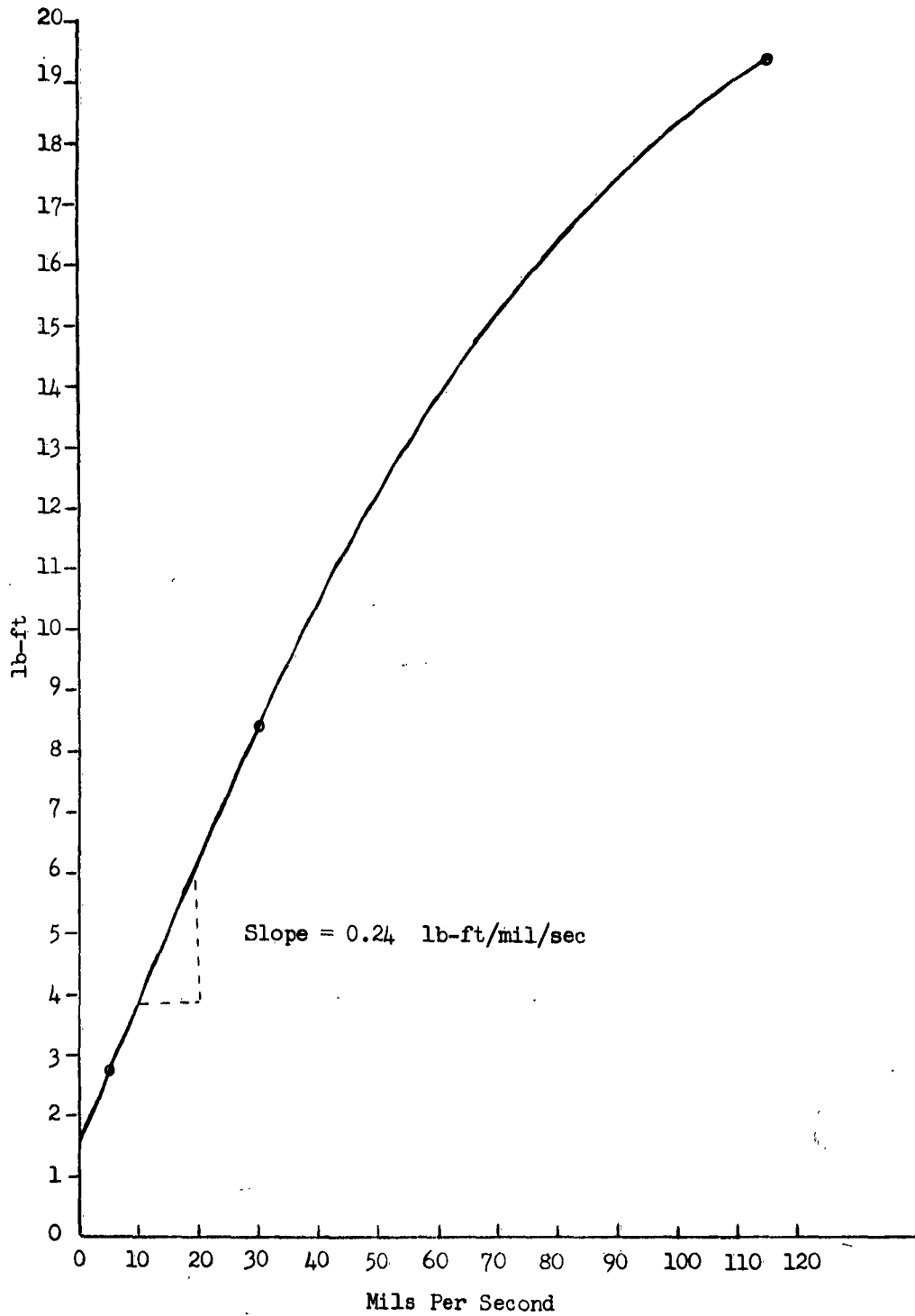Fig. 5. VISCOUS DAMPER

Rotating Discs

Stationary Discs

Fig. 6. VISCOUS TORQUE AND EQUIVALENT ANGULAR RATE

10% or less. Given a constant velocity gradient, then

$$\tau = \eta \; A \; \frac{v}{d} \; r \qquad (1)$$

where η = viscosity = 2.5 x 10^6 centistokes x 10^2 x .98 gm/cc

A = incremental area

v = tangential velocity of A

r = moment arm of A

d = spacing between plates

τ = torque

For the case of one-side loading on a disc, neglecting edge effects (which may be rather large), consider a ring of width Δr
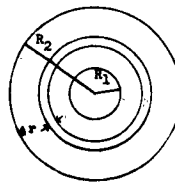
$$\Delta \tau = \Delta F \cdot r \qquad (2)$$

$$\Delta F = \eta \; \Delta A \frac{v}{d} \qquad (3)$$

$$\Delta A = 2 \pi r \Delta r \qquad (4)$$

$$V = 2 \pi r \omega, \quad \omega = \text{angular rate} \qquad (5)$$

Substitute (3), (4), (5) into equation (2)

$$\Delta \tau = \eta \cdot 2 \pi r \Delta r \cdot 2 \pi r \omega r \qquad (6)$$

Integrate over the inside and outside radii of the disc:

$$\tau = \frac{4 \pi^2 \eta \omega}{d} \int_{R_1}^{R_2} r^3 \; dr \qquad (7)$$

For two side loading, then,

$$\tau = \frac{2 \pi^2 \eta \omega}{d} (R_2^4 - R_1^4) \cong \frac{2 \pi^2 \eta \omega}{d} R_2^4 \qquad (8)$$

where $R_2 > 3 R_1$

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By utilizing the appropriate geometry, edge effects can be taken into account by a similar procedure; however, fringing becomes more important. The fringing effect can probably be considered small for the case where all stators are unlocked, because then both stators and rotors revolve at essentially the same rate.

In another design, shown in Figures 7 and 8, a similar procedure was used, with results that agreed closely with predictions, although no rigorous analysis was made of fringing effects.

Although this class of devices has several valuable features, such as ease of design and continuous rotation, it has several disadvantages such as large size, and high cost attendant to the use of the heavy fluids. The lighter silicone fluid is considerably less expensive, and when one considers that temperature and gunner variations may require a spread of 6:1 in adjustment of the damper, some other solution to the problem of supplying damping without adding appreciable coulomb friction would be appealing. One possibility is a van arrangement, as shown in Figure 9. Although this scheme does not allow continuous rotation, many applications do not require continuous rotation; ease of adjustment is certainly a strong point in its favor.

An element that has not been discussed up to this point, but which is extremely important in the design of a lightweight mount, is the compliance that couples the inertia to the damping. Consideration of Figure 10 will show that rigidity is essential in order to take full advantage of the damping. Table 1 lists, among other characteristics, the compliance of the Human Engineering Laboratories mount, which is definitely too high. It is not known to what value this should be reduced; it is estimated that compliance should be reduced at least five times.

Another undesirable feature of compliance of the mount is the manner in which it prevents effective suppression of firing transients by viscous damping. These transients arise from (a) recoil which tends to displace the mount as a whole, (b) recoil whose line of action does not pass through the centers of rotation of the gimbal, thus affecting the tube only, (c) changes in the center of gravity of the tube-missile system during firing, (d) changes in the moment of inertia of the system as the missile progresses down the tube, and (e) operator flinching during firing. The sum of these effects is noticeable on the firing data.
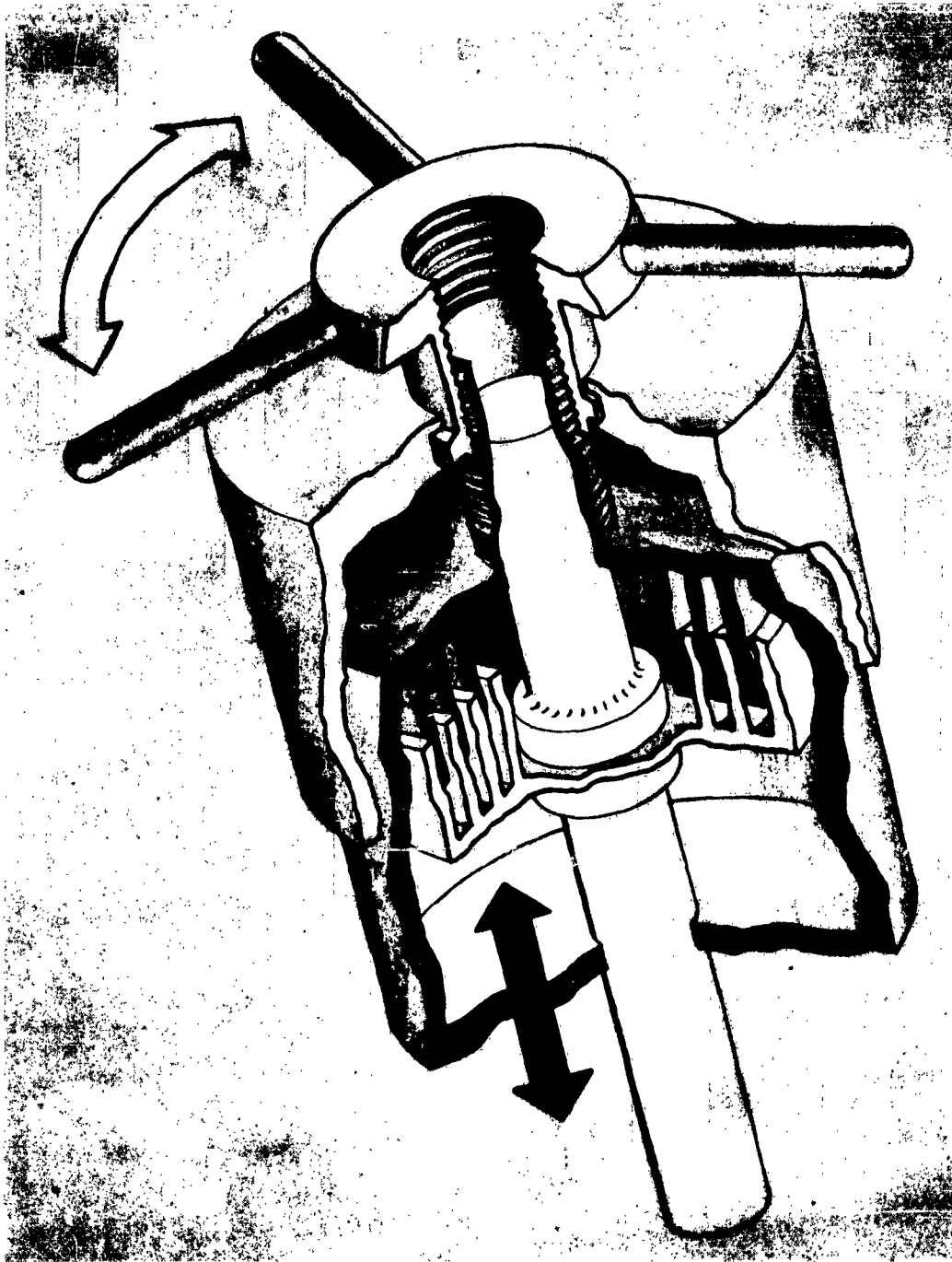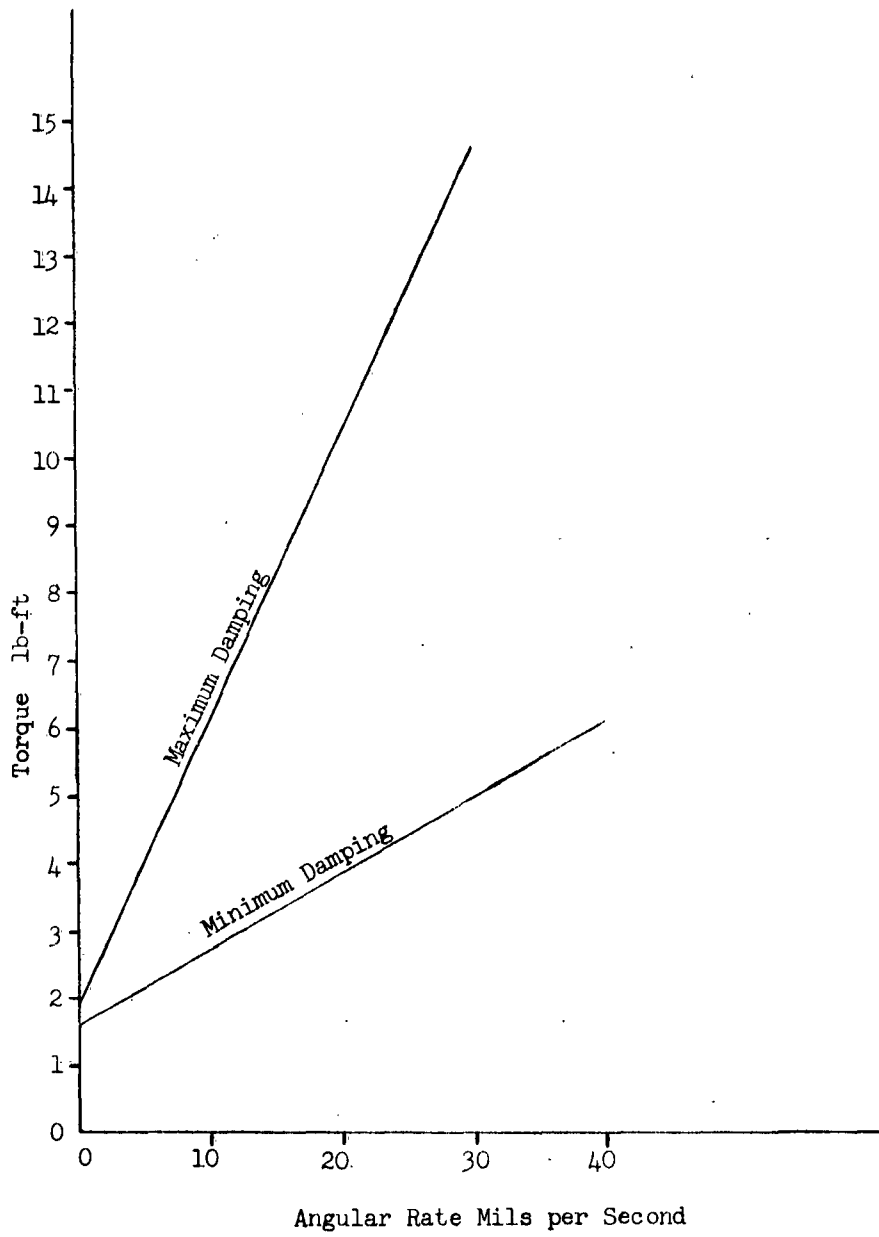
Fig. 7. VISCOUS DAMPER
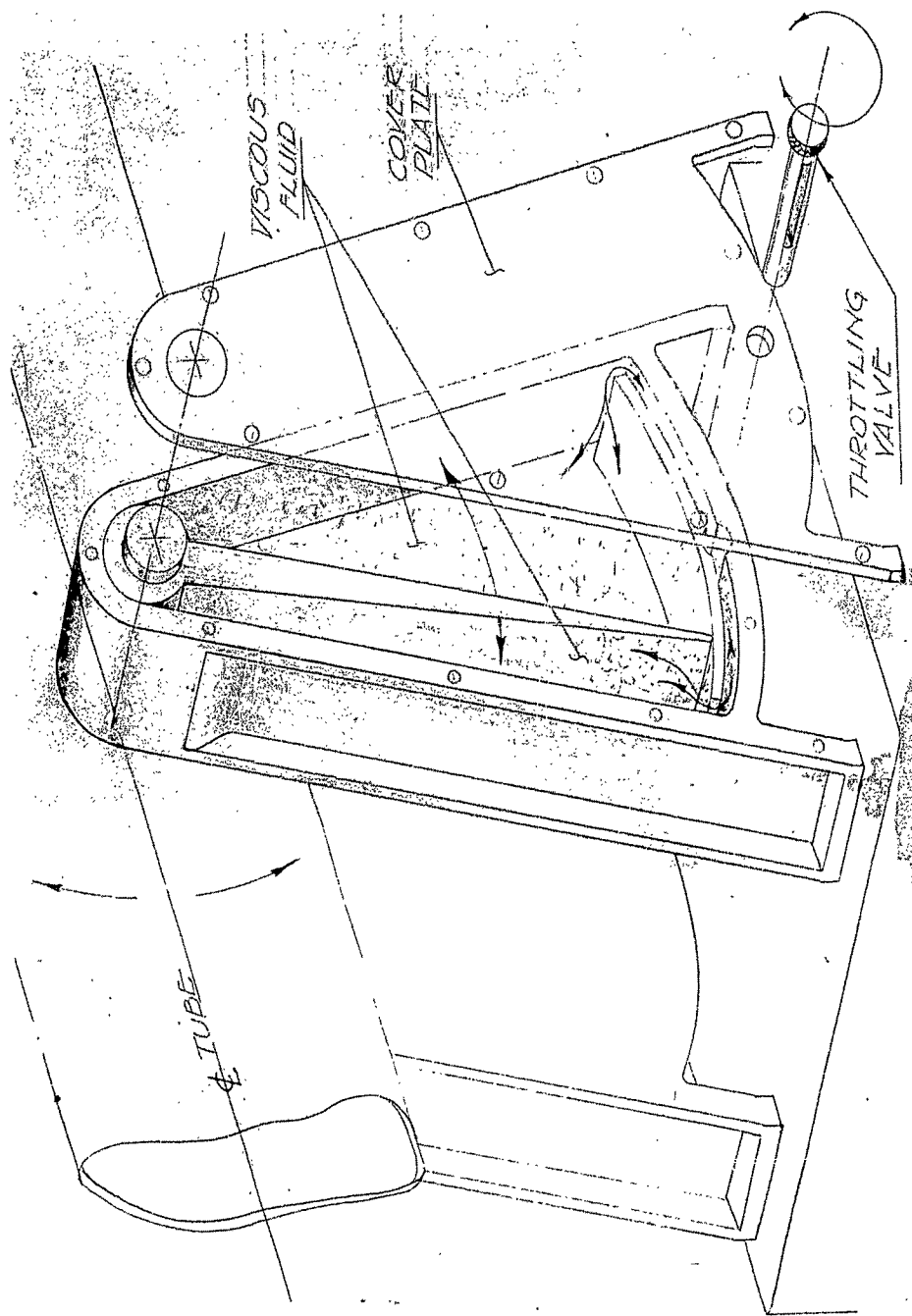
Fig. 8. VISCOUS TORQUE AND EQUIVALENT ANGULAR RATE

VISCOUS FLUID

COVER PLATE

THROTTLING VALVE
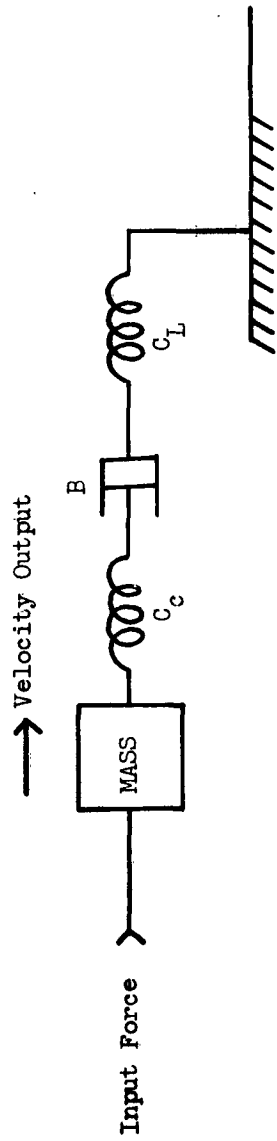
℄ TUBE

Fig. 9 VISCOUS DAMPER

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Fig. 10. SYSTEM SCHEMATIC

APPENDIX B

An unusual technique was used to superimpose a grid on the
data film. A small reticle, approximately the same size as the
frame size, was lightly cemented with Duco (or its equivalent) to
the fiducial markers or some other convenient protuberance in the
data camera. The object here is to place the reticle, which will
have opaque lines on a transparent background, immediately in
front of the film emulsion, so that the opaque lines cast a sharp
shadow on the film. The reticle can be made conveniently from a
high contrast, good resolution film. A master reticle negative
is made by photographing white thread against a dark background,
in the pattern desired, and several times larger than the finished
size. This master reticle is then photographed at a distance
determined by the relation:

$$\frac{d}{D} = \frac{F_1 \sin \alpha}{F_2}$$

where d = distance between two grid lines on master

D = distance between master and photographing lens

F_1 = focal length of lens of data camera

F_2 = focal length of lens photographing the master, and

α = angle to be subtended by the distance between two grid
lines on the finished reticle.

This system was employed in two types of cameras at frame
rates up to 64 fps. Several thousand feet of film have been passed
over a reticle with no apparent ill effects on either the film or
the reticle. Some of the nice features of this method are its low
cost, light weight, and the ease with which special reticles may be
constructed.

APPENDIX C

ANALYSIS OF VARIANCE

1. The representative score used for this analysis was the radial RMS for the last 7 seconds of tracking for each trial.

2. The symbols chosen for the several factors were:

M -   Mounts

M_1 -   Free Mount

M_2 -   Rate Mount

M_3 -   Hand Wheel Mount

D -   Direction

D_1 -   From left to right

D_2 -   From right to left

S -   Speed

S_1 -   5 mph

S_2 -   30 mph

G_n -   Gunners $n = 1, 2, 3, \ldots 6.$

3. Summary of Analysis of Variance:

	ss	df	MS	SS error	df	MS error	F	P<
M	6.9828	2	3.4914	0.6699	10	0.06699	52.12	.005
S	1.4187	1	1.4187	0.6172	5	0.12345	11.49	.025
D	0.4439	1	0.4439	0.1376	5	0.02752	16.13	.025
MxS	1.205	2	0.6025	0.3716	10	0.03716	16.21	.005
MxD	0.4490	2	0.2245.	0.4444	10	0.04444	5.05	.05
DxS	0.0422	1	0.0422	0.4222	5	0.08444	0.50	--
MxSxD	0.1285	2	0.0643	0.3687	10	0.03687	1.74	.25

4. Multiple Comparisons:

	M_1	M_2	M_3	k = 2	k = 3 for P $<$ .05	
$\bar{s}$	0.402	0.375	1.049	0.166	0.174	
s_1	0.352	0.325	0.726	0.157	0.164	
s_2	0.453	0.425	1.372	0.251	0.262	

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U. S. Army Human Engineering Laboratories
Aberdeen Proving Ground, Maryland
GUNNER TRACKING BEHAVIOR AS A FUNCTION OF
THREE DIFFERENT CONTROL SYSTEMS
Robert T. Gschwind. Technical Assistance, Richard R.Kramer

Technical Memorandum 2-63   Unclassified
AMCCMS Code 5520.12.471

An investigation was conducted to determine the
magnitude and character of tracking errors occurring
after firing a rocket at a moving target from a light-
weight mount. Six professional gunners with varying
degrees of experience fired 3.5-inch rockets from each
of three distinct types of tracking devices, viz., a
two-Hand Wheel system, an electrical rate system, and
a viscously damped, integrated position control system
(Free Mount).

There was no significant difference in magnitude of
tracking error between the Free Mount and the rate
system, with both achieving 0.5 mils RMS error across
all conditions of angular rate. The two-Hand Wheel
system was significantly worse with 1.0 mils error at
low rates and 2.0 mils error at high rates.

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