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CONTROL-MOTION STUDIES OF THE PBM-3 FLYING BOAT IN ABRUPT PULL-UPS

By Henry A. Pearson and Leland K. Smull

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NACA

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MEMORANDUM REPORT

for

Army Air Forces, Materiel Command

and

Bureau of Aeronautics, Navy Department

CONTROL-MOTION STUDIES OF THE PBM-3 FLYING BOAT IN ABRUPT PULL-UPS

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INTRODUCTION

For some time it has been felt that the strength requirements of control surfaces should be placed on a more rational basis and that they should in some manner be related to the acceleration, rolling, and yawing performance required of the airplane on which they are installed. Due to the fact that existing requirements were easily applied and few failures of control surfaces had occurred until recently, the rational methods, although they were available, were not used. This was in part due to the fact that they were, in general, too long and, in addition, that the critical types of control motion were not known.

Recent failures in which both the horizontal and vertical tail surfaces were apparently involved have resulted in a desire to use the more rational methods in spite of the extra work that will be necessary. A first step, that of simplifying the theoretical methods as much as possible, has already been undertaken (reference 1). So far the results have been confined to horizontal tail, and they show, as would be expected, that for the maneuver condition the up tail load is dependent mainly upon the normal acceleration while down tail load depends upon the rate at which the controls are moved. Both the maximum up and down tail loads, however, vary with the static stability of the airplane.

The second phase of the problem, that of determining the rate of control movement, is not amenable to analytical treatment since it will depend both upon physiological and psychological factors. Thus, in order to obtain data on this point, it is necessary to determine by actual test the most critical stick motions which might be used in the different airplane categories.

To obtain such data, the best procedure would be to determine by statistical methods the rates of movement actually used by various pilots in performing maneuvers. If, however, it could be shown that the control-surface loads are reasonable, even allowing for the most rapid rates possible, then a quicker and certainly more conservative method, as far as the controls are concerned, would be to use the greatest rates which a pilot can impose.

The present paper is the first of a number of control-motion studies that are to be made in flight covering a range of types and sizes of modern airplanes. The control-motion studies reported herein were made on a large flying boat, the PBM-3. The control mechanism of this airplane is typical of the cable-type systems that are incorporated in large transport, cargo, or bomber airplanes as well as those employed in flying boats. For this reason, the data presented are probably representative for most large airplanes utilizing cable systems.

The tests reported herein were conducted at the Naval Air Station during the period from September 1 to October 1, 1942, with the cooperation of the Bureau of Aeronautics, Navy Department.

APPARATUS

Airplane. - The essential characteristics of the PBM-3 flying boat (fig. 1) are as follows:

Span, feet	118
Length, feet	80
Wing area, square feet	1407
Horizontal tail area, square feet	242
Elevator area, square feet	96.2
Balance area	23.55
Distance from center of gravity to center of lift of the horizontal tail, feet	41.0
Design gross weight, pounds	46,500

Recording instruments. - Two control-position recorders were used to determine the motion of the elevator. One was mounted between the rudder pedals (fig. 2) to measure the longitudinal motion of the control yoke which was the motion impressed on the elevator. The other was mounted in the rear gunner's turret (fig. 3) and was attached directly to the elevator torque tube to measure the angular movement of the elevator. The control wheel on the co-pilot's side was replaced with one equipped to record control force (fig. 4).

In addition to the above instruments, a standard NACA recording accelerometer and a turn meter to record the pitching velocity of the airplane were also installed at the center of gravity of the airplane (fig. 5). One-tenth second timing was impressed on all the records to give time histories of the recorded motions, accelerations, and velocities.

In addition to the results recorded by the above instruments, observations were made at the start of each run of the pressure altitude, indicated airspeed, and manifold pressure from the airplane's instruments.

METHOD AND RESULTS

The program of tests carried out on the PBM-3 divided itself naturally into three phases: The first phase was a determination of the stability characteristics in steady level flight and the computation of possible tail loads in maneuvers; the second phase was a series of ground runs in which the elevator was moved as rapidly as possible; and the third phase was the actual pull-ups in flight. The relation of these various phases to each other will become apparent from the following:

<u>Stability runs and preliminary computations</u>. - A number of unusual factors were involved in carrying out the present

program and as a result careful preparations were made to reduce any hazards that might occur. Since the tail loads were expected to be quite severe in the type of pull-ups to be made, it was necessary to compare the loading conditions for which the tail was actually designed with calculated loadings using the fastest possible stick motions. For such calculations a number of aerodynamic parameters were necessary. Some of these were determined in flight while others were obtained from wind-tunnel data. The flight tests required to determine these parameters consisted of a number of steady flight runs at various airspeeds throughout the speed range with the center of gravity at 25 and $34\frac{1}{2}$ percent of the mean aerodynamic chord. In these tests two power conditions were used, one being approximately full power while the other was with the engine throttled. The pertinent data obtained during these tests are given in table 1 wherein up elevator and up tab are designated by minus signs. The elevator setting given is that measured at the tail and so does not include any cable stretch; the tab setting listed is that necessary for trim under the given flight condition.

The data obtained from these tests, together with that obtained in subsequent ground tests on the rates of stick motion, enabled a computation to be made of the maximum tail load likely to be encountered in flight. The computed values of the tail load using maximum rates were then compared with the design tail loads in order to determine whether the pull-ups could be made with safety.

As a matter of record, the load factor and tail-load variation computed for an actual rapid pull-up are given in figure 6 for the center-of-gravity location of 28 percent mean aerodynamic chord. The computed values were obtained by the method of reference 1 in conjunction with the actual elevator motion measured in flight and the characteristics listed in table 2. The limit design loads for the horizontal tail as obtained from the manufacturer are given in table 3. For comparison, the loads computed for the pull-up of figure 6 are also given in this table.

Ground runs. - Following the steady flight stability tests, a series of abrupt elevator deflections were made, with the ship sitting on the ramp, in which time histories were obtained of the elevator motion impressed at the stick and that obtained at the torque tube. In the first series of ground tests, instructions were given to four different pilots to move the controls as rapidly as possible with no restriction as to the amount of travel. The variation of the measured quantities obtained in these tests are given in figure 7.

In addition to the above tests, a series of three pull-backs was made, in which the control was to be moved as rapidly as possible, subject to the restriction that the control be moved less than 12 inches. This restriction was imposed in order to simulate what was believed might actually occur in flight where the pilot would be constrained, by the airplane's characteristics as well as by both physiological and psychological factors, to smaller deflections. The results of this short series of tests are given in figure 8 where the elevator angle impressed at the stick and the control travel are represented by a single curve with different ordinate scales.

In addition to the point-by-point evaluation of the film records that was necessary to obtain the time history given in figures 7 and 8, the maximum rates were obtained directly from the record films by measuring the maximum slopes. The maximum rates so determined, which may differ slightly from that obtained from the plotted time histories, are summarized in table 4 in the columns labelled "ground runs."

Pull-ups. - Upon completing the ground runs and determining that the tail loads to be encountered did not exceed the design values, a series of 24 pull-ups were made from power-on level flight. The pull-ups were made at three initial airspeeds of approximately 184, 200, and 220 miles per hour at each of two center-of-gravity positions, namely 26 and 30 percent mean aerodynamic chord. These pull-ups were all made within a period of less than 30 minutes by the pilot who was most familiar with the ship.

The instructions given to the pilot were to pull up to approximately a 3g acceleration, at each of the three speeds and two center-of-gravity positions, using two types of control motion. A repeat run was to be made for each condition. In both types of control motion, the pull-back was to be made as rapidly as possible only in one type, designated type II; an effort was to be made to move the stick more than was necessary and then to prevent overshooting 3g by an abrupt control reversal. In the other type, designated type I, the control was to be moved as rapidly as possible only to the amount necessary to give 3g.

Figure 9 is the record of the accelerations obtained with the V-G recorder during the 24 pull-ups. Figures 10 through 21 give the time histories of the recorded quantities measured in the pull-ups. They are arranged in a manner so that comparison can be made directly between the so-called type I and type II pull-ups. The maximum control forces measured are listed with each of the runs.

The maximum rates of elevator and stick movement measured directly from the record films are shown in figure 22 plotted against indicated airspeed. Different symbols are used to designate both the type of elevator motion and the center-of-gravity position. In figure 23, the increments in elevator movement required to effect the pull-ups are plotted versus airspeed for the two center-of-gravity positions used.

DISCUSSION

As may be seen from the time histories of the ground runs (fig. 7), there was an initial lag between the control and the elevator motion. During the initial accelerating period of the control column, the cable and pulley system stretched storing potential energy which, during the latter part of the pull-back, caused the elevator to catch up and, in some cases, actually to lead the control. At the end of the motion, the stored kinetic energy caused both the control and the elevator to travel beyond the static limits of the system.

Examination of the maximum rates of control movement attained (see table 4) in the ground tests indicated no marked or consistent differences between the various pilots. The maximum rates obtained ranged from 82 to 111 inches per second, all of which were slightly higher than the average maximum value of about 80 inches per second, quoted in reference 2.

When a mental restriction as to the amount of travel was imposed (see fig. 8), the maximum rates obtained were only about one-third of that obtained with no restriction. It is believed that the imposition of a restriction as to the amount of travel will always result in a somewhat smaller maximum rate although the reductions may not be as drastic as in the present case. For the PBM-3 the spring of the control system was such as to cause a rapid feedback during the latter part of the motion which, in some cases, was greater than the pilot could control. This may have influenced the results somewhat in the case of the restricted motions.

The results of the flight tests (figs. 10 to 21) all have one thing in common, namely that the elevator angle reached was considerably less than that impressed at the stick. As shown in figure 23, at 184 miles per hour the ratio of the actual to the impressed angle is about 0.45, whereas at the highest speed tested (220 miles per hour) this ratio is about 0.37.

The springiness of the control system also had a marked effect on the "type of motion." As may be seen from figures 10 to 21, the only difference actually obtained between the two types is that the pilot, in trying to carry out instructions, pushed forward more in the type II pull-up than in the type I pull-up. The "give" in the system as well as the disadvantageous position in which the pilot had his arms, with the control moved back about 10 inches, prevented him from using more elevator than would normally be required for a 3g pull-up. The results shown in figure 23 clearly indicate this variation in that at a given speed the elevator angle increment is the same regardless of the type of motion that was specified.

The maximum rates of control movement (see fig. 22) decreased with an increase in the initial airspeed. A comparison of the rates obtained on the ground with those taken in flight (table 4) indicates the flight values to be on the average about one-third less. This is somewhat contradictory to previous thoughts (based on the ground test reported in reference 2) on the subject that, provided the forces are within the pilot's limitation, they have little if any effect on the movement. It is possible in the present case that, in spite of the pilot's statement that he had no hesitancy in pulling the control back as rapidly as possible and the observer's opinion that this was done, some psychological element entered.

It is thought that the decrease in rate of movement with airspeed that is shown in figure 22 is due to the increased aerodynamic resistance encountered as the speed increased. The decrease in rate that is shown with the center of gravity moved to the rear is thought to be due to fatigue on the part of the pilot since the tests with the center of gravity at 30 percent were performed after those with the center of gravity at 26 percent and all of them were performed within a period of 30 minutes.

CONCLUSIONS

The results of the tests indicate:

1. That the elasticity of the elevator control system of the PBM-3 was such as to limit the obtainable acceleration to about 3g for center-of-gravity positions in the usual operating range, that is, 26 to 30 percent mean aerodynamic chord, and for the range of airspeeds covered by the tests.

2. That the maximum rates of stick movement obtained in the ground tests did not vary materially with various pilots; the rates measured tended to be slightly higher than previously measured value.

3. That the maximum measured rates of stick movement obtained in flight were about one-third less than on the ground; for design purposes a maximum rate of 20π inches per second should be adequate for airplanes of this size.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 12, 1942.

REFERENCES

1. Pearson, Henry A.: Derivation of Charts for Determining the Horizontal Tail Load Variation with Any Elevator Motion. NACA ARR, Jan. 1943.

2. Hertel, Heinrich: Determination of the Maximum Control Forces and Attainable Quickness in the Operation of Airplane Controls. NACA TM No. 583, 1930.

TABLE 1

DATA RECORDED DURING STABILITY RUNS

Weight 45,550 c.g. @ 25% Power on

V mph	RPM	Alt, ft.	Elev setting	Tab setting
104	2295	8100	-4.6	+2.4
115	2295	8360	-2.1	+ .2
126	2295	8590	+0.6	-1.0
138	2295	9120	2.6	-1.2
150	2305	9450	3.3	-2.0
161	2300	9430	4.2	-2.2
172	2310	9400	4.6	-2.6
184	2310	9030	5.4	-3.0
196	2310	8700	5.65	-3.1

Weight 44,350 c.g. @ 34.5% Power on

V mph	RPM	Alt., ft	Elev setting	Tab setting
104	2295	7350	1.9	- 2.0
115	2290	7800	4.6	-2.8
126	2300	8000	5.1	-3.4
138	2300	8250	5.8	-3.1
150	2305	8450	6.5	-3.1
161	2310	8600	7.1	-3.5
172	2310	8500	7.1	-4.0
184	2315	8200	7.4	-4.2
196	2315	7600	7.6	-4.5

Note: Tab setting recorded is that required for trim, minus indicates up angle

Weight 45,550 c.g. @ 25% Power off

V mph	RPM	Alt. ft.	Elev. setting	Tab setting
104	2295	3800	-4.6	+ 2.1
115	2295	3900	-1.2	0
126	2300	4000	1.0	-0.8
138	2320	4100	2.8	-1.2
150	2320	4400	3.6	-2.7
161	2320	4400	4.2	-2.0
172	2320	5000	4.6	-2.4
184	2320	5500	5.3	-2.5
196	2305	7000	5.5	-3.0

Weight 44,350 cg @ 34.5% Power off

V mph	RPM	Alt., ft.	Elev. setting	Tab setting
104	2295	4400	2.8	-2.8
115	2295	4400	4.6	-3.4
126	2295	4400	5.5	-3.4
138	2295	4500	6.9	-4.0
150	2285	4800	6.5	-4.0
161	2305	4900	6.9	-4.0
172	2305	5300	7.4	-4.0
184	2305	6000	7.6	-3.9
196	2305	6400	7.7	-4.0

TABLE 2

CONSTANTS USED IN COMPUTATIONS OF PBM-3 FLYING BOAT

S	wing area, square feet	1407
S_t	tail area, square feet	242
S_e	elevator area, square feet	96.2
b	wing span, feet	118
b_t	tail span, feet	28
x_t	distance from aerodynamic center tail to center of gravity, feet	-41.0
k_Y	radius of gyration in pitch, feet	15.0
W	gross weight at time of pull-up, pounds	45,000
$\frac{dC_L}{d\alpha}$	slope of airplane lift curve including thrust component and with tail surfaces in place	5.0
K	empirical damping factor	1.1
η_t	tail efficiency factor, q_t/q	1.0
$\frac{dC_{L_t}}{d\alpha_t}$	horizontal tail lift curve slope/radian	4.3
$\frac{dC_{L_t}}{d\delta}$	elevator effectiveness slope	1.83
m	airplane mass, slugs	1400
A	aspect ratio b^2/S	9.9
ρ	air density (5800 feet), slugs per cubic foot	0.002
$\frac{d\epsilon}{d\alpha}$	downwash factor	0.53
$\frac{dC_{m_t}}{d\alpha_t}$	rate of change of elevator moment with camber	-0.1

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Table 3

Summary of limit loading conditions for horizontal tail of PBM-3

	Angle of attack load		Deflected control surface load		Net load	
	Right	Left	Right	Left	Right	Left
Balancing load c.g. forward 24.4 %	-2769	-2769	2882	2304	182	170
Balancing load c.g. aft 35.5 %	-2893	-2893	3640	3485	692	692
Vertical gust load					4431	4431
Horizontal gust load					-331	331
Maneuver load					4431	4431
Landing inertia load					6505	6505
Tail loads computed from recorded stick motion. c.g. 26% MAC					1980 -2262	1980 -2262
Tail loads computed from recorded stick motion. c.g. 28% MAC					2060 -2094	2060 -2094
Tail loads computed from recorded stick motion. c.g. 30% MAC					2445 -2089	2445 -2089

Note: Minus indicates down load

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Table 4

Elevator control motion rates measured on PBM-3

Stick angle rate deg/sec				Stick travel rate in./sec.				Elevator angle rate deg./sec.			
Flight		Ground runs		Flight		Ground runs		Flight		Ground runs	
		Full Throw	Short Throw			Full Throw	Short Throw			Full Throw	Short Throw
202	134	141	70	77	51	84	27	67	46	132	60
174	147	154	88	66	56	92	34	65	50	141	61
176	159	160	89	67	61	95	34	68	49	135	65
193	169	186		74	65	111		70	48	133	
176	176	134		67	67	80		50	49	171	
170	126	161		65	48	96		69	43	181	
192	142	138		73	54	82		47	44	183	
160	165	158		61	63	94		60	54	180	
155	132	147		59	50	87		42	42	185	
163	116	164		62	44	98		45	41	180	
144	130			55	50			51	41		
148	150			57	57			45	45		

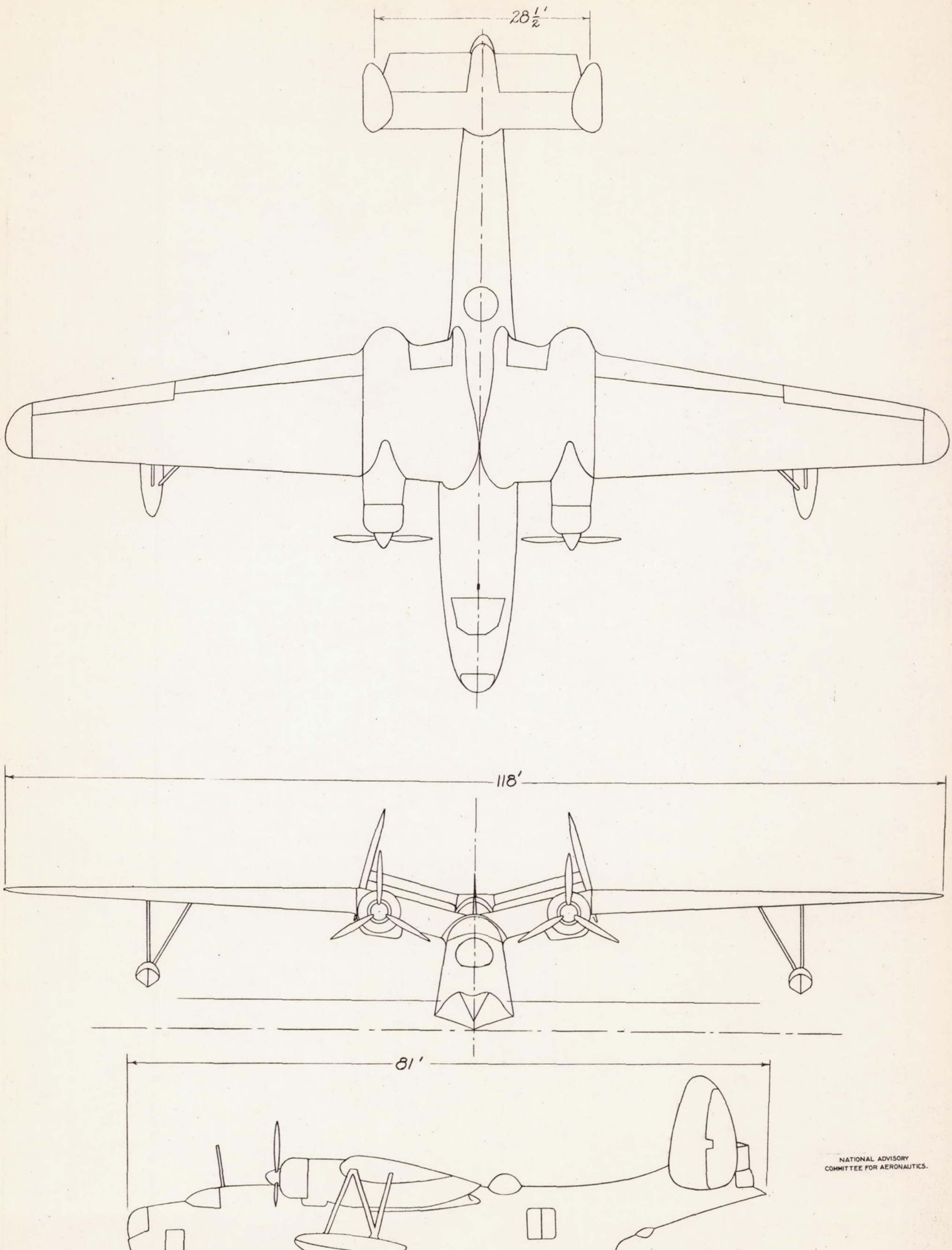

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Figure 1 - Three-view line drawing of PBM-3 airplane.

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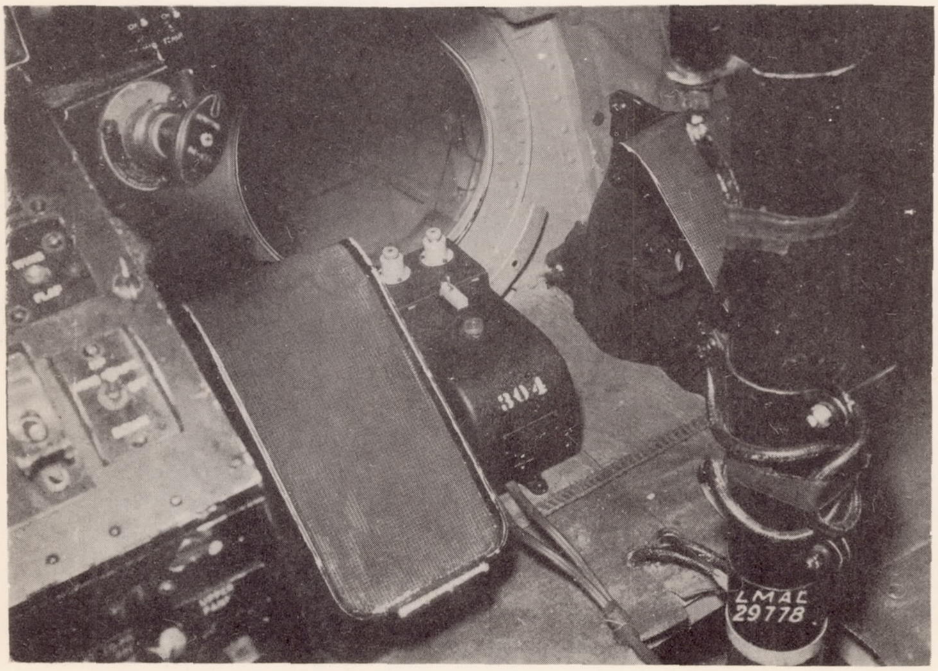

Figure 2.- Control position recorder for recording stick motion.

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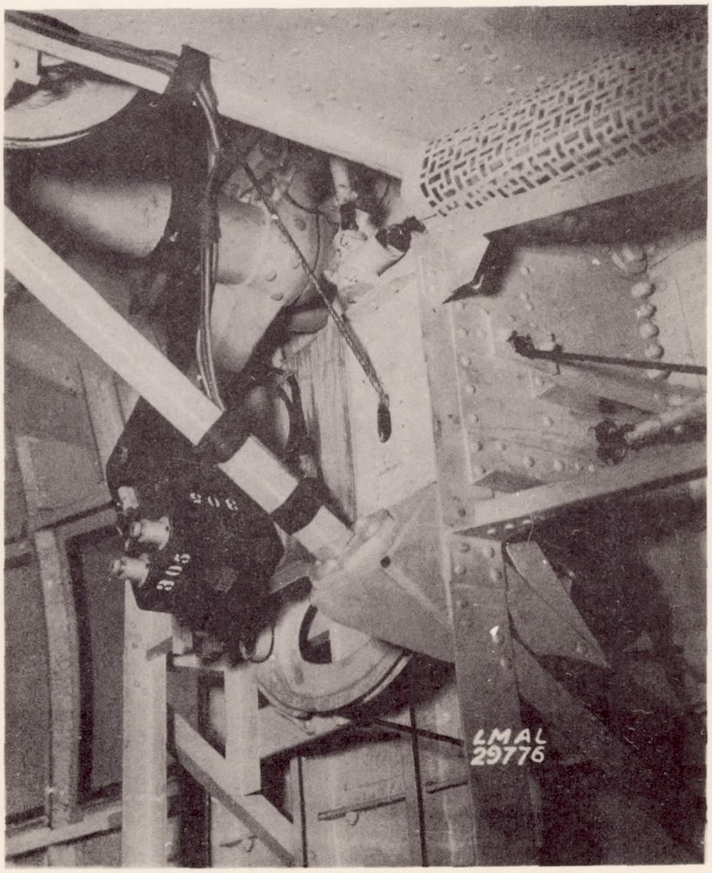

Figure 3.- Control position recorder for recording elevator motion.

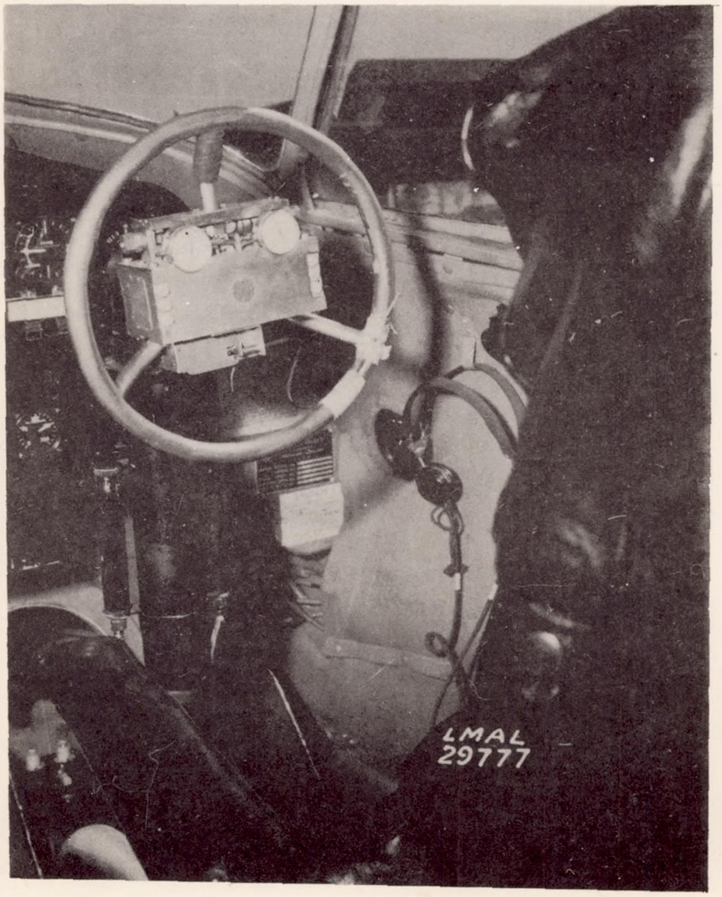

Figure 4.- Wheel control force recorder mounted on stick for recording maximum control force.

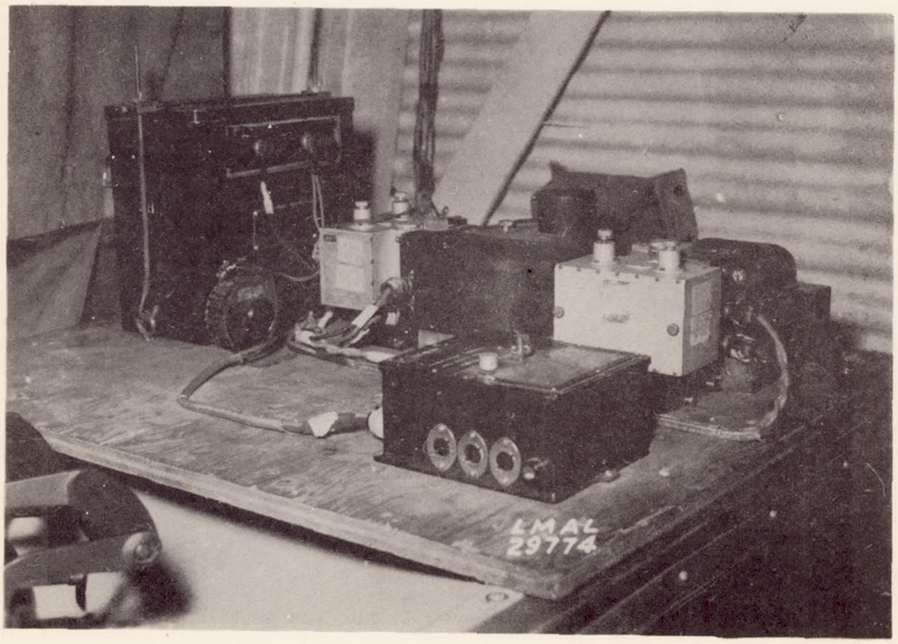

Figure 5.- Recording accelerometer, recording turnmeter and timer mounted at center of gravity of the airplane.

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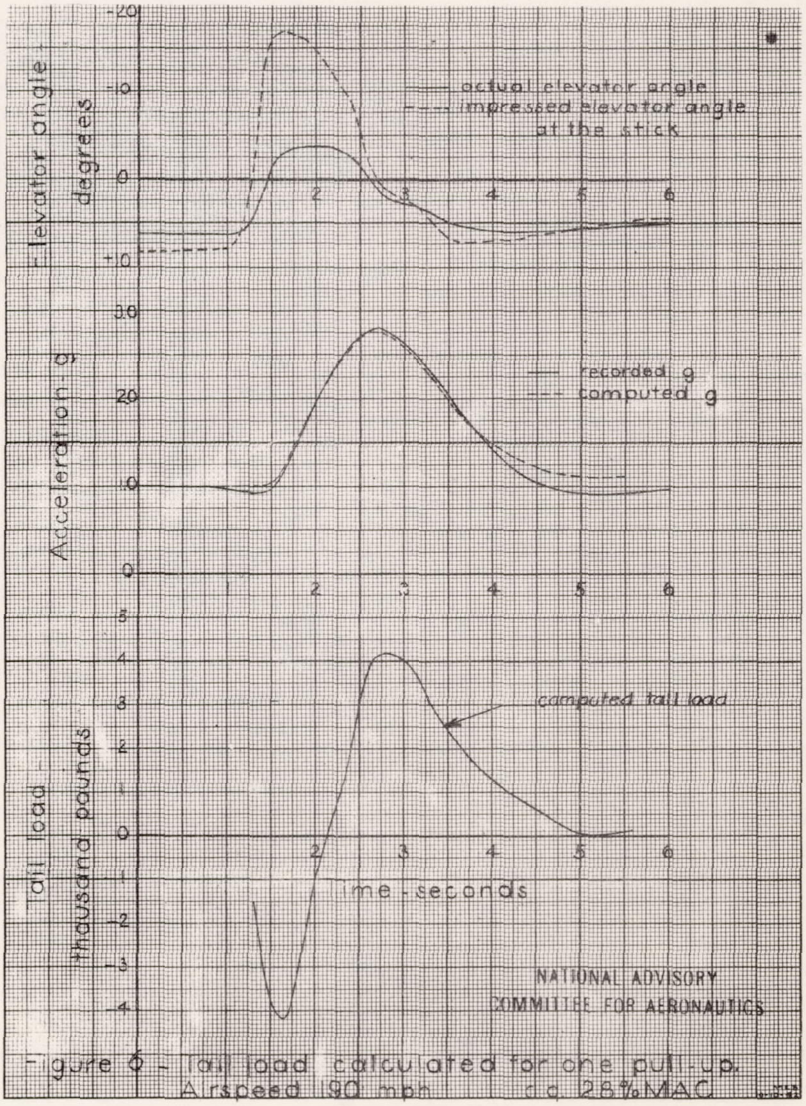

Figure 6 - Tail load calculated for one pull-up. Airspeed 190 mph c.g. 28% MAC

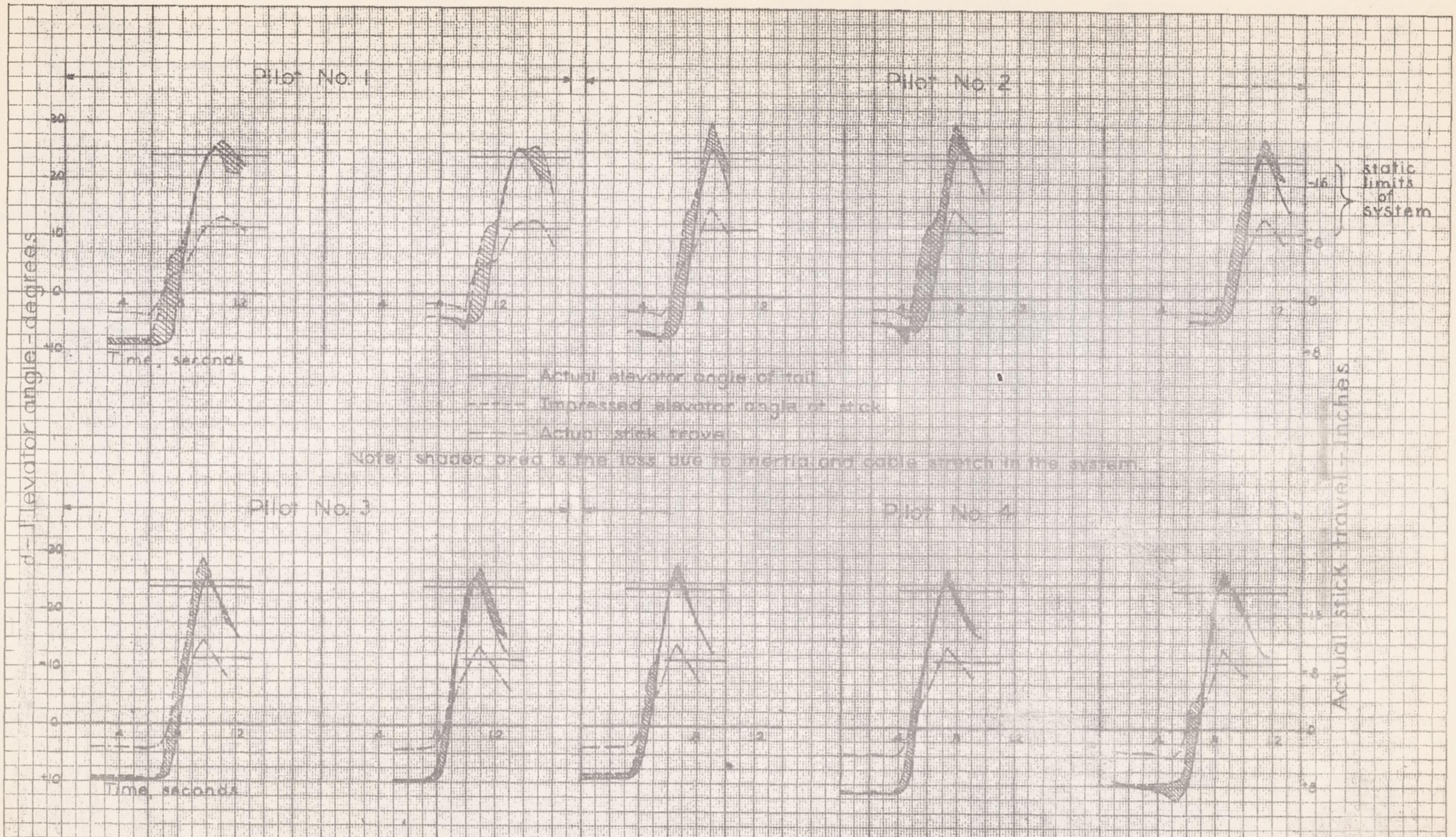

Figure 7 – Variation of elevator and stick travel on PBM-3 as measured on the ground for rapid pulls made by four pilots.

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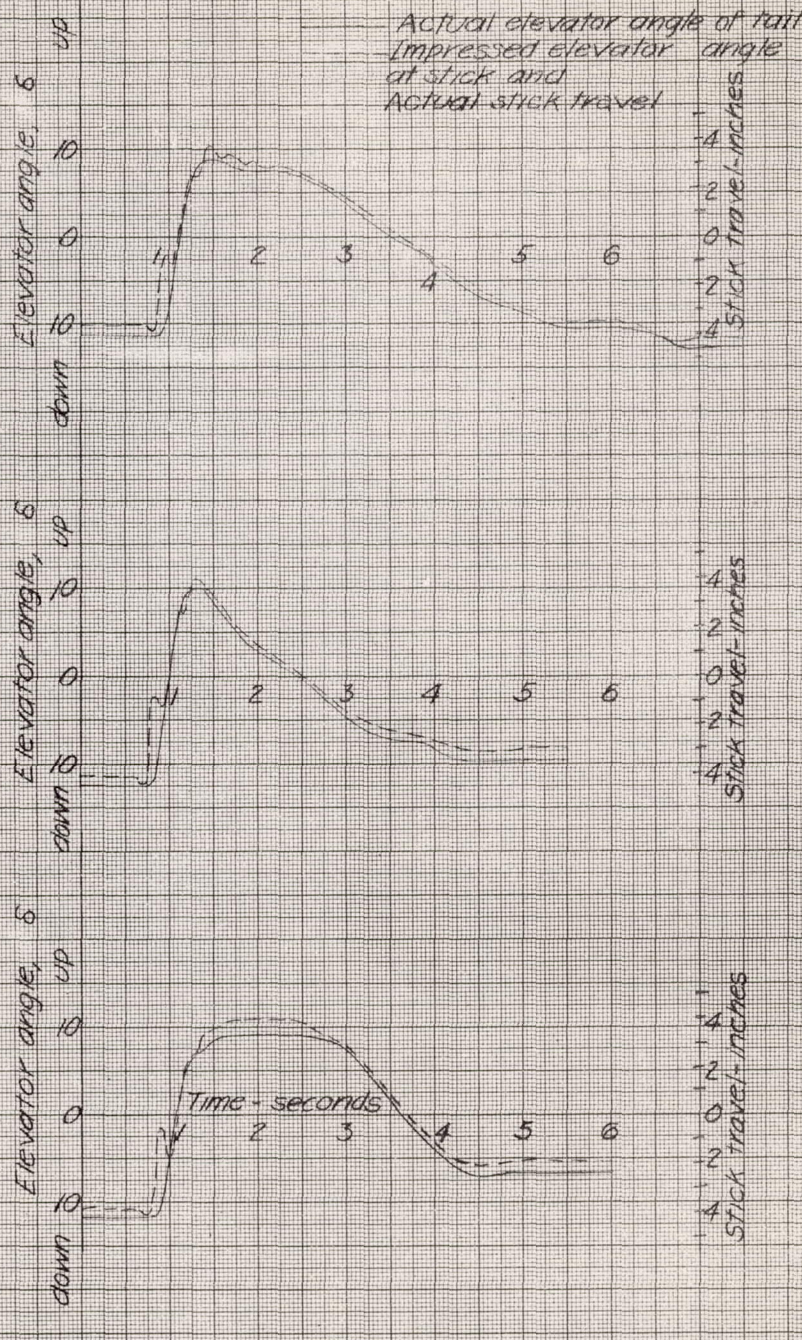

Figure 8-Variation of elevator and stick travel on PBM-3 as measured on the ground for rapid pulls of a restricted throw.

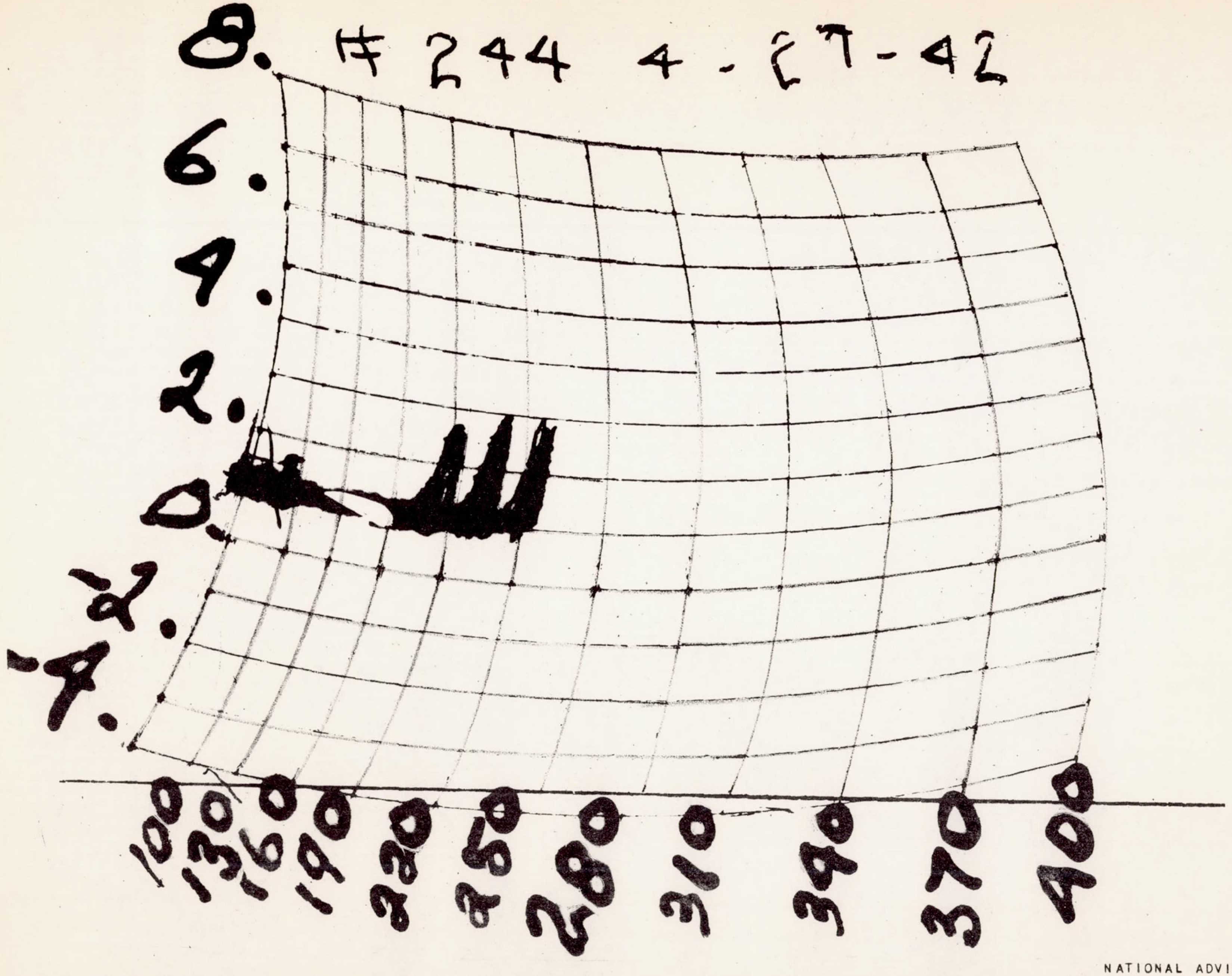

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Figure 9.- V-G records obtained in 24 pull-ups on PBM-3 airplane.

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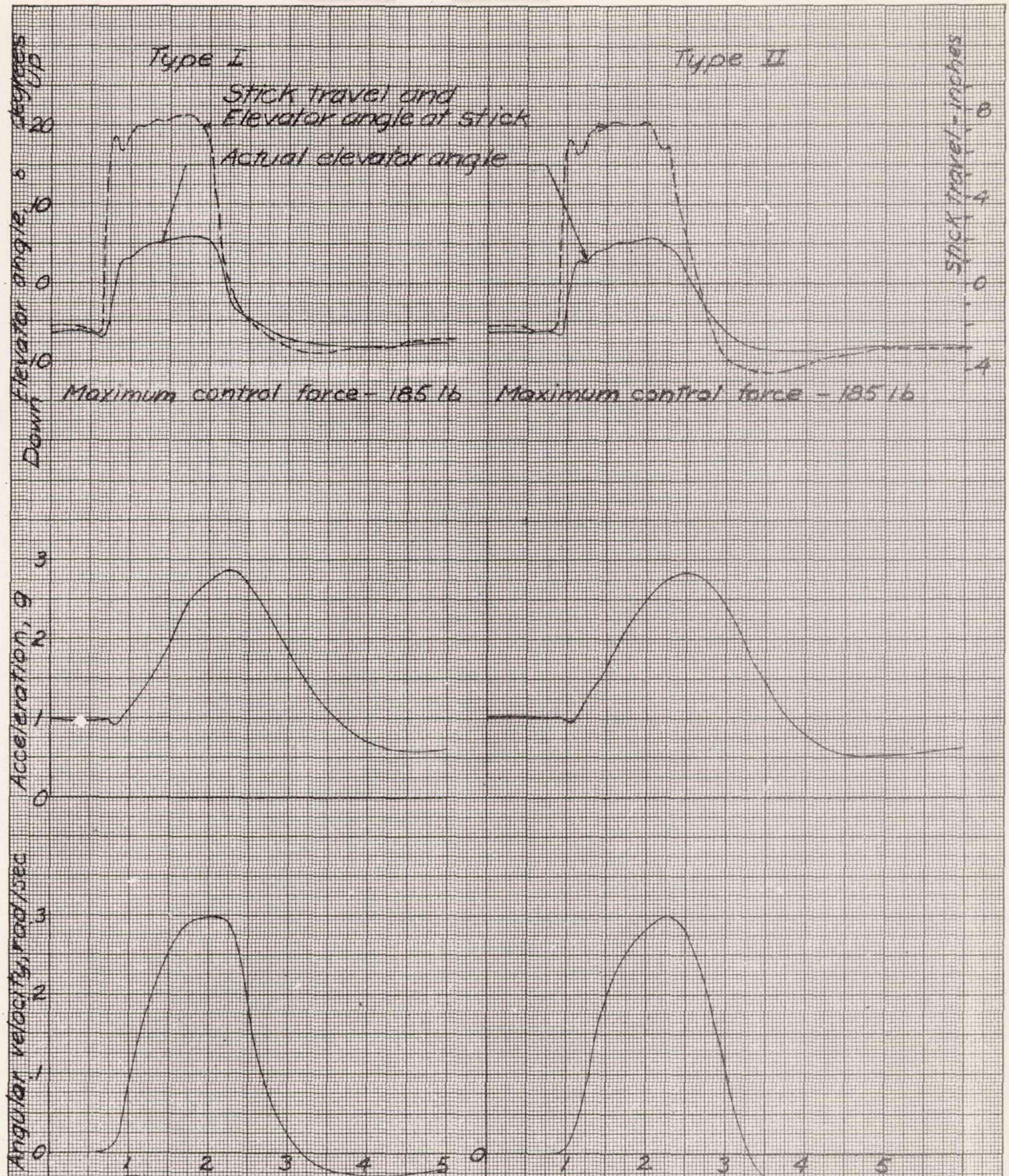

Figure 10.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 26 % MAC, initial airspeed - 184 mph.(ind.)

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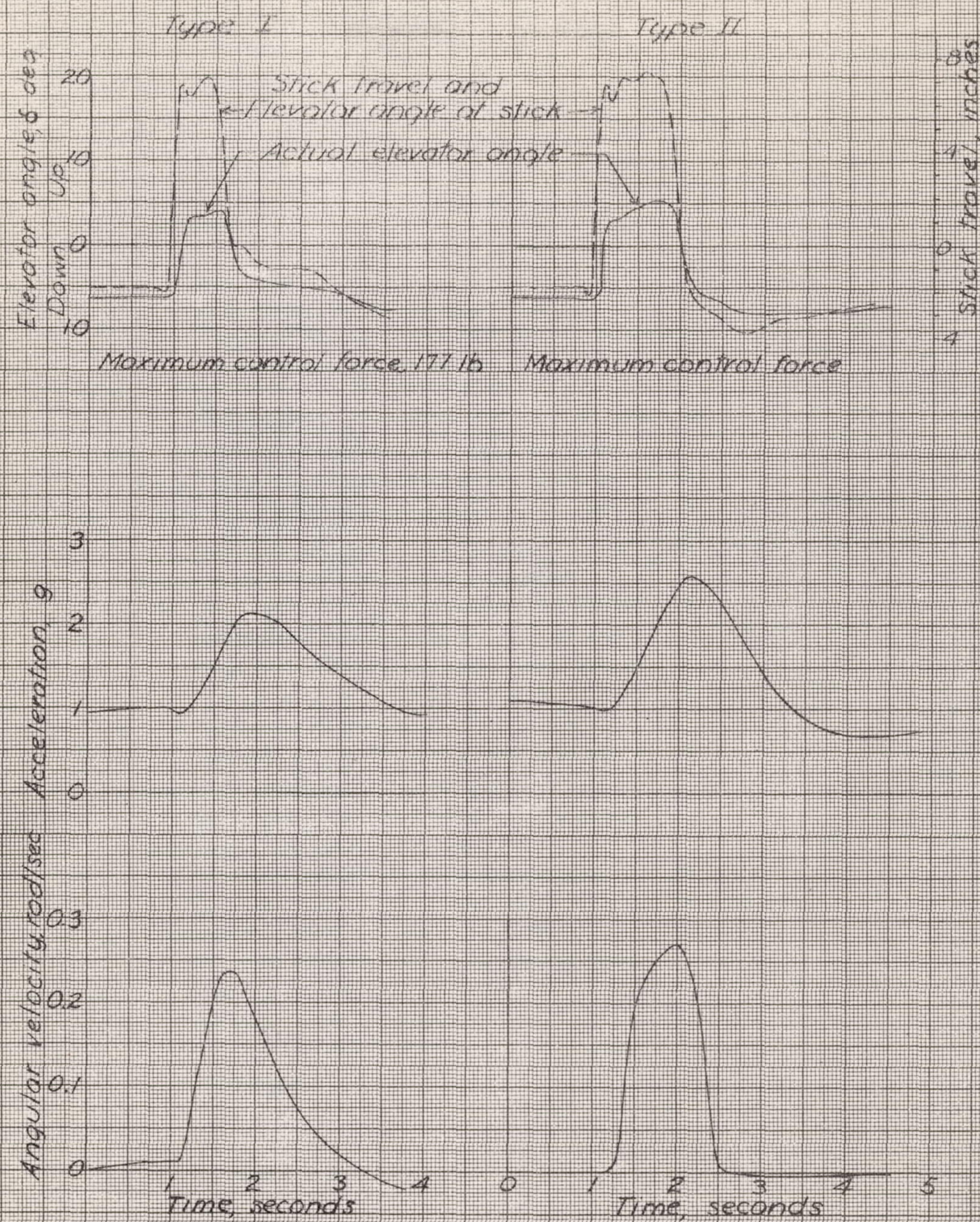

Figure 11.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. cg at 26% MAC. Initial airspeed 184 mph,(ind)

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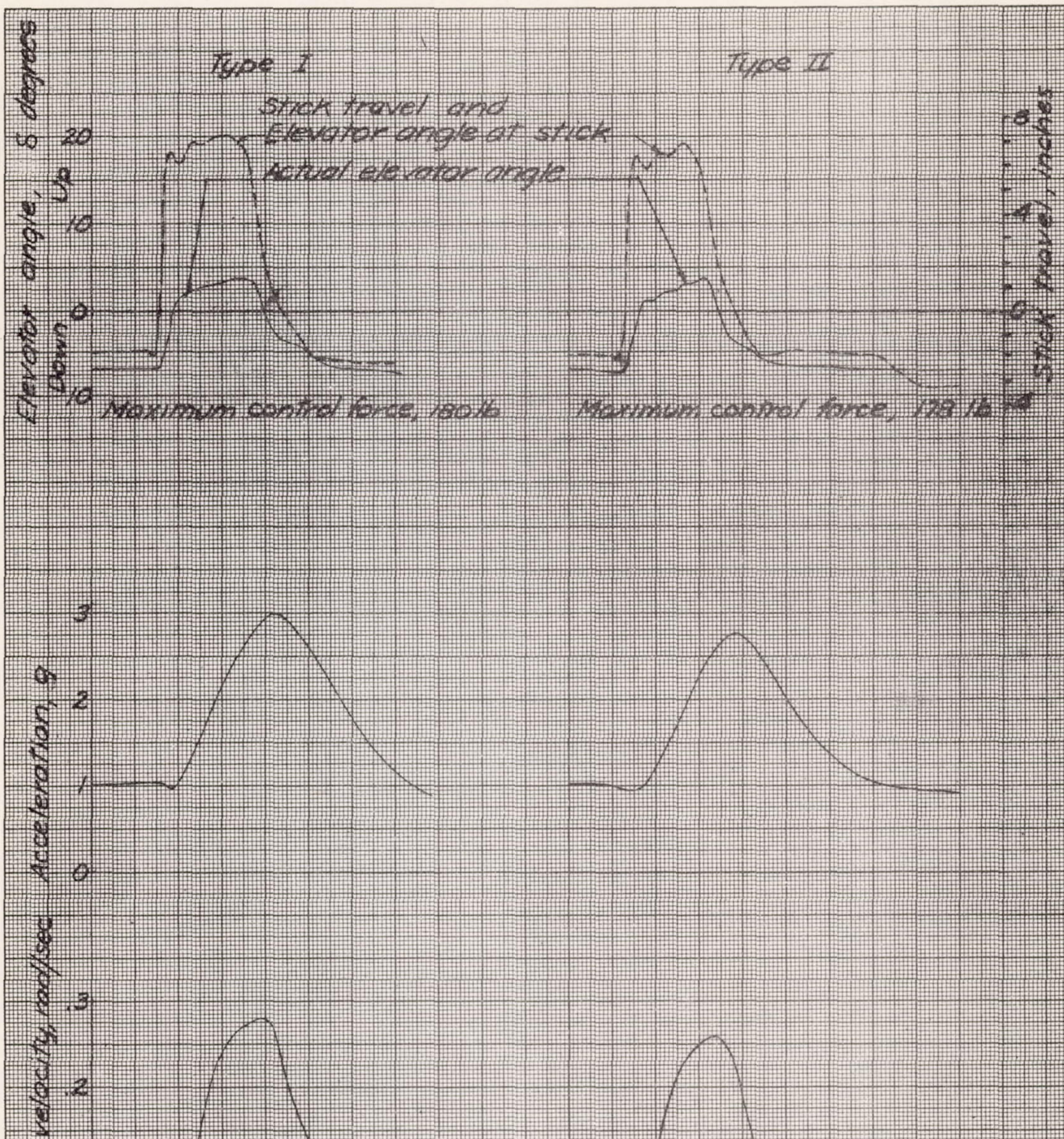

Figure 12.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 26 % MAC, initial airspeed-201 mph. (ind.)

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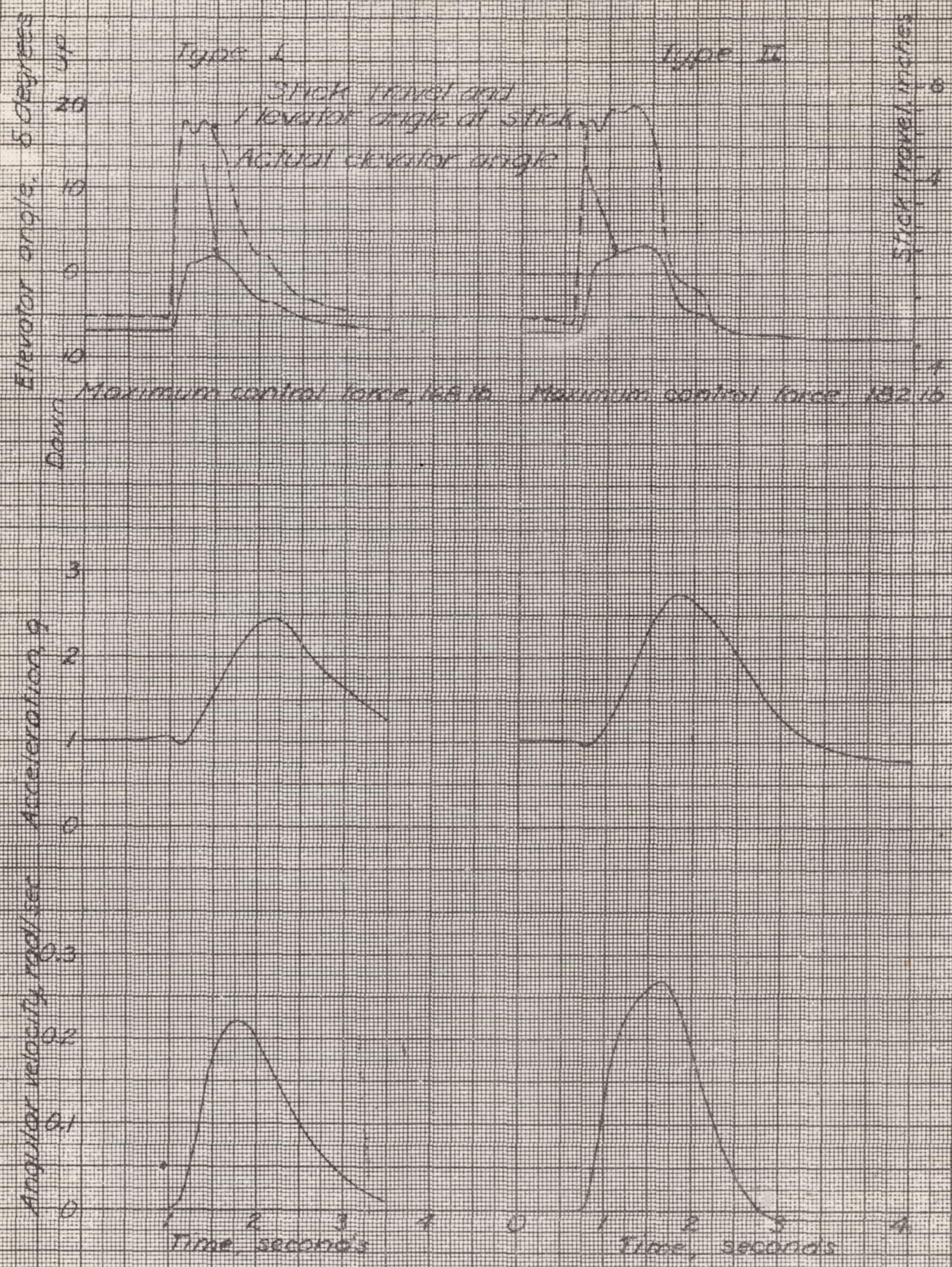

Figure 13.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 26% MAC, initial airspeed 201 mph (ind.)

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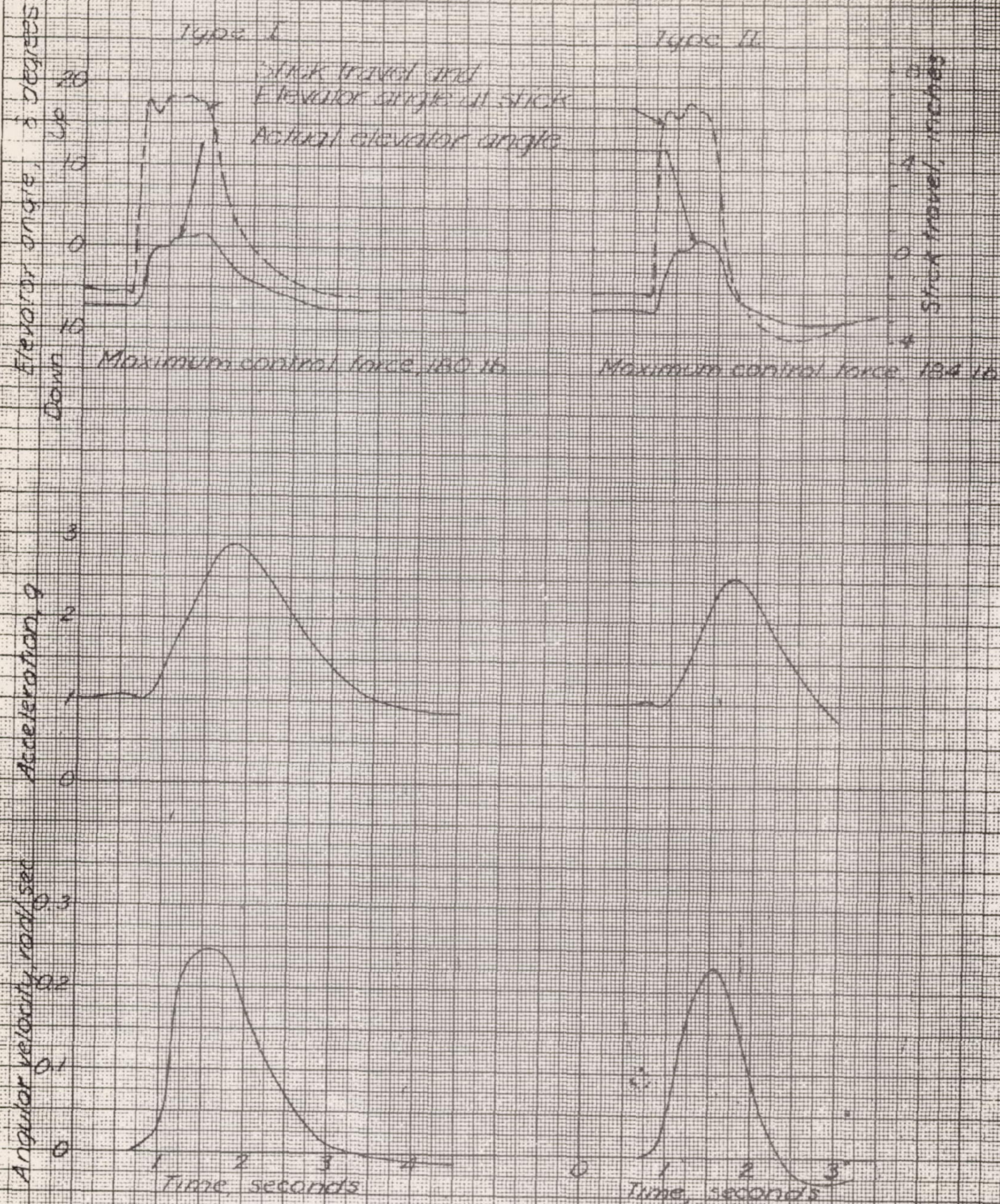

Figure 14.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 26 % MAC., initial airspeed 219 mph (ind.)

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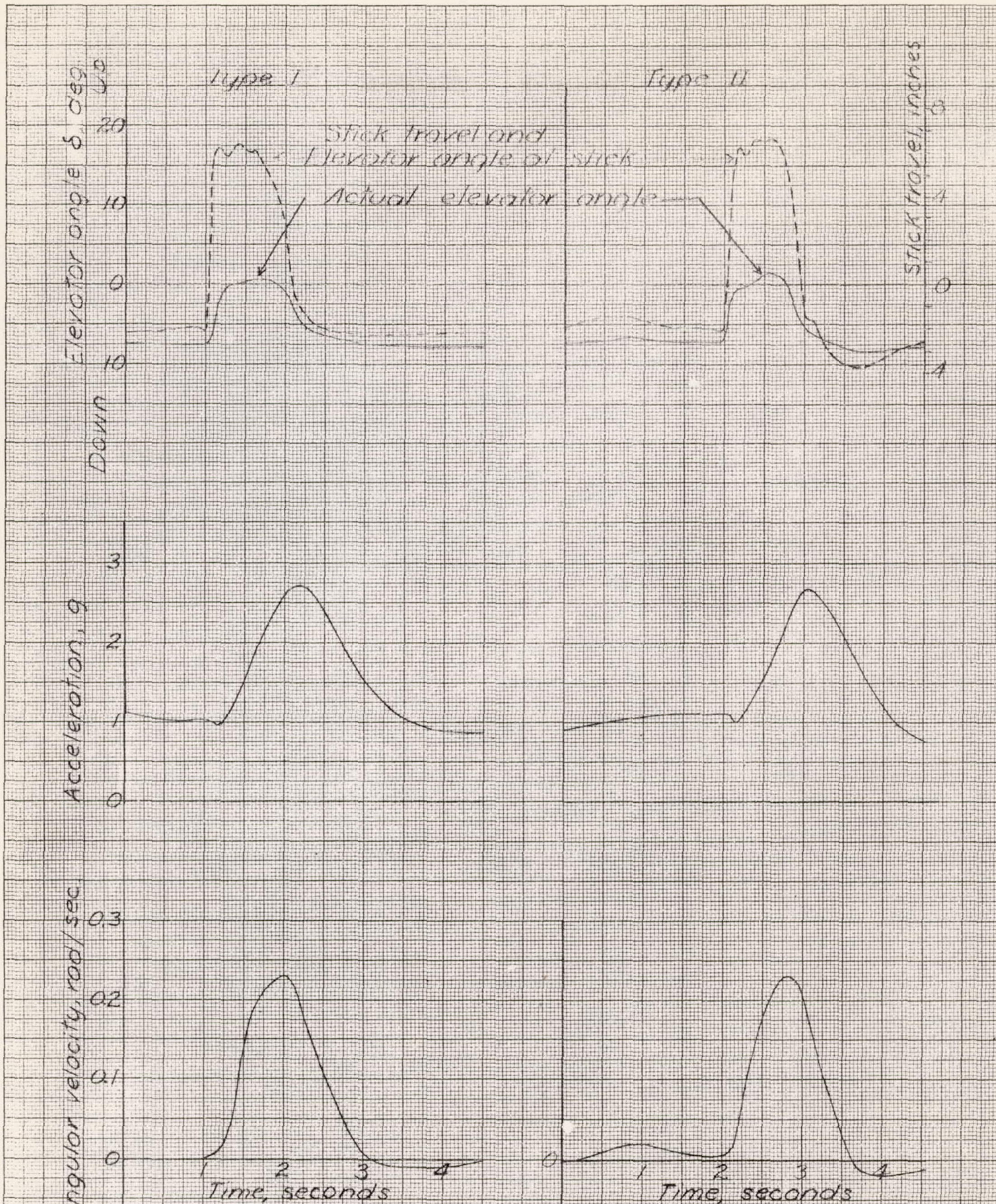

Figure 15 - Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 26% MAC Initial airspeed - 219 mph, (ind)

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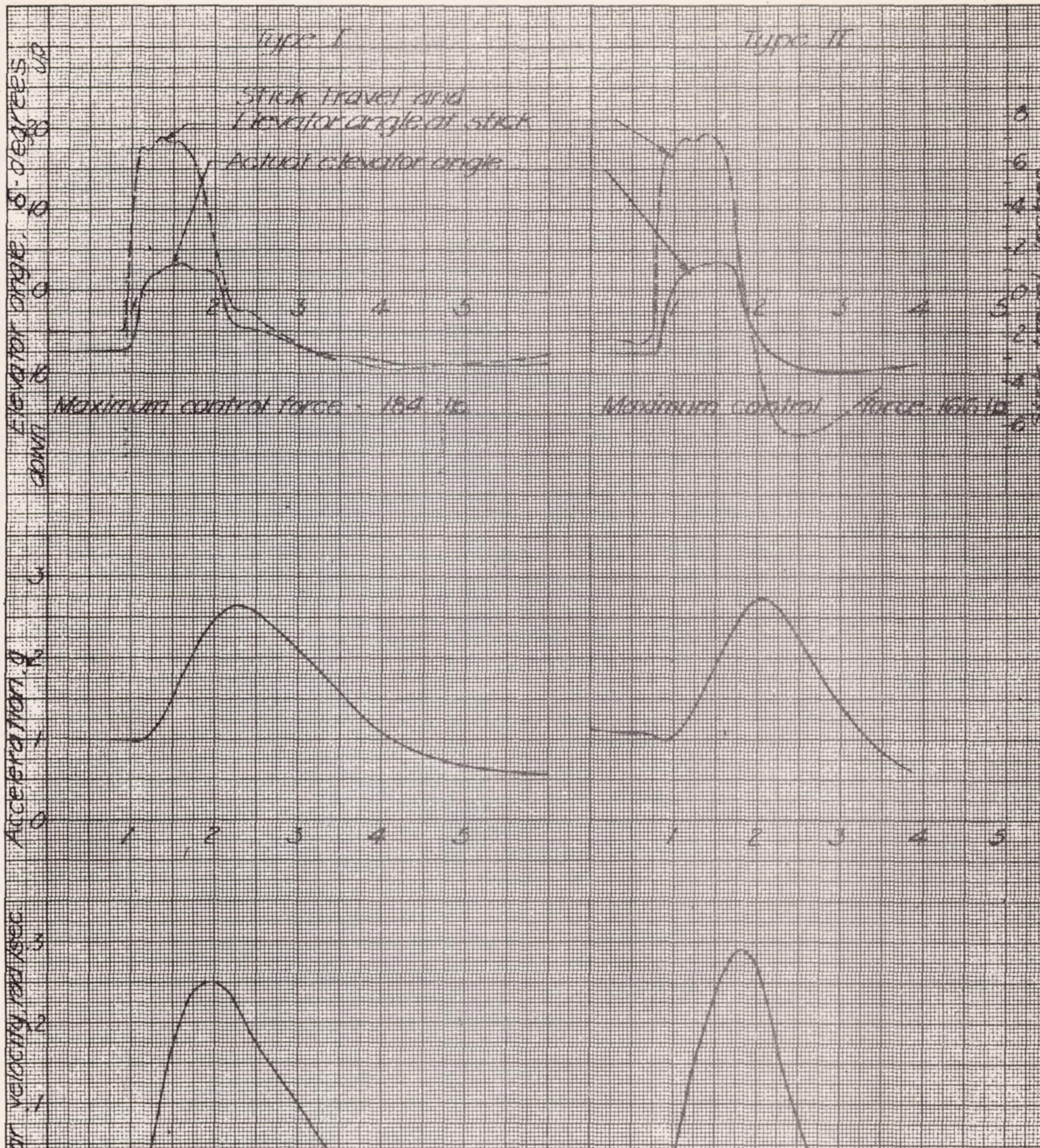

Figure 16.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30 % MAC, initial airspeed - 184 mph. (ind.)

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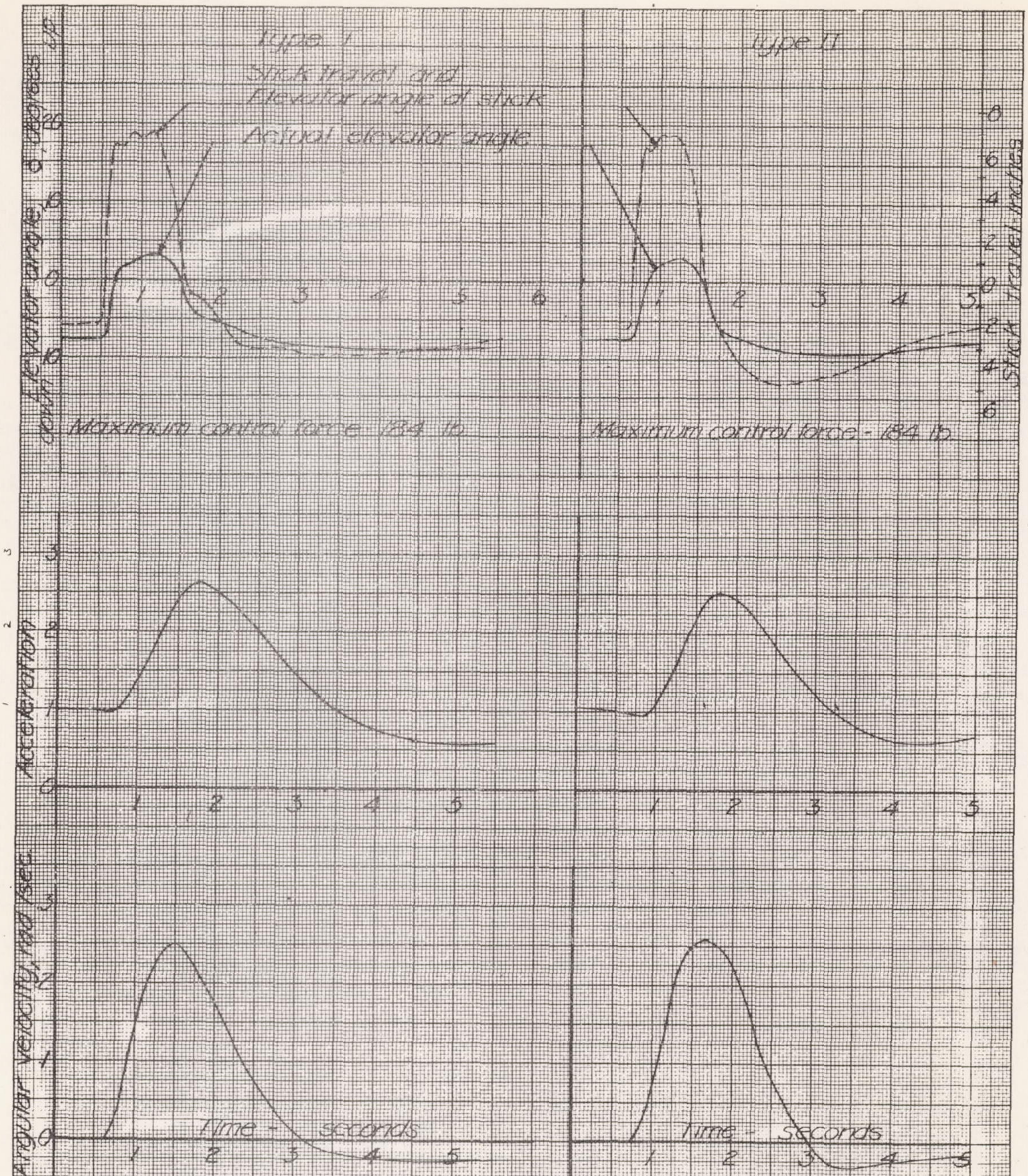

Figure 17.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30 % MAC, initial airspeed - 184 mph (ind.)

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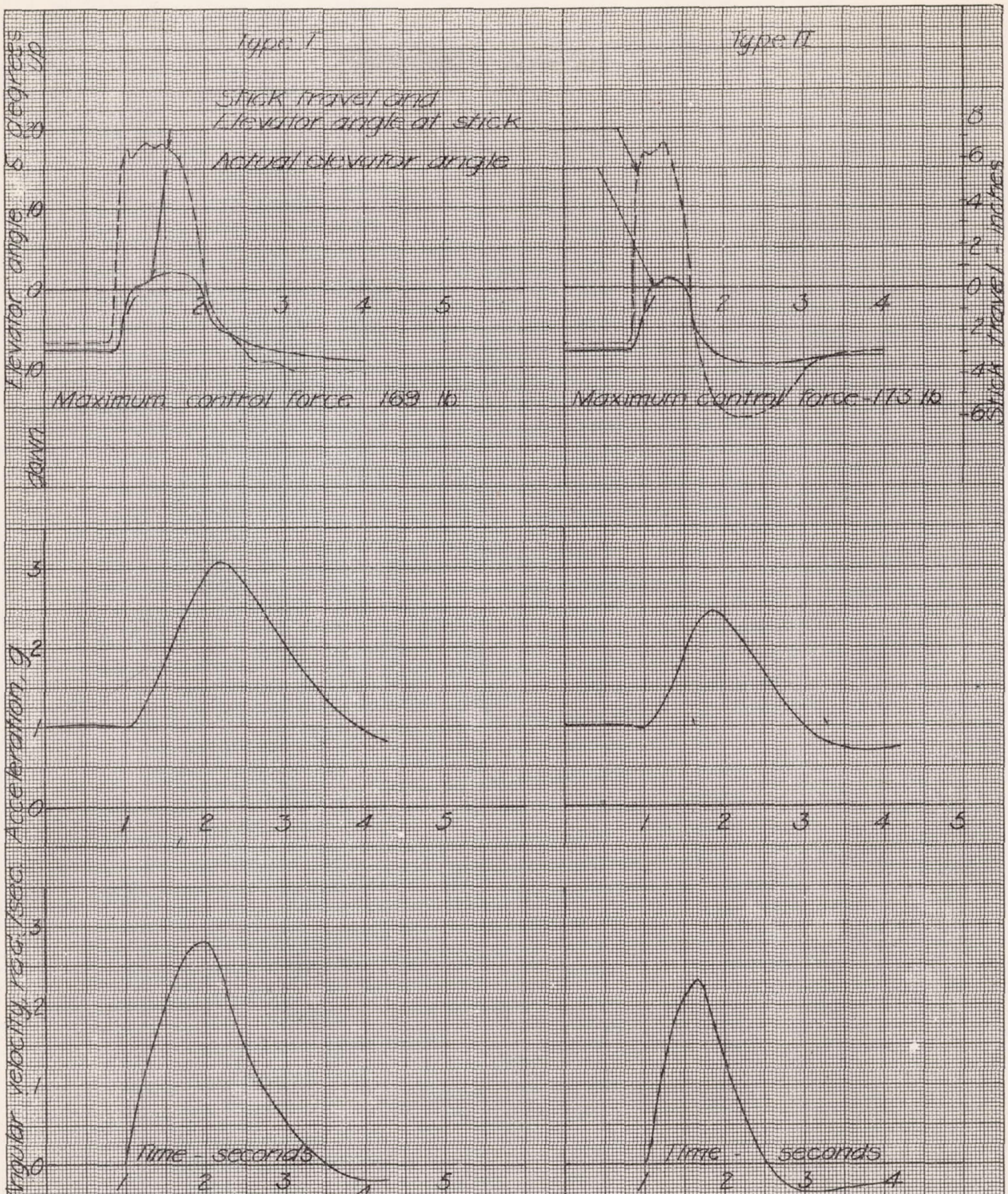

Figure 18.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30 % MAC, initial airspeed - 201 mph. (ind.)

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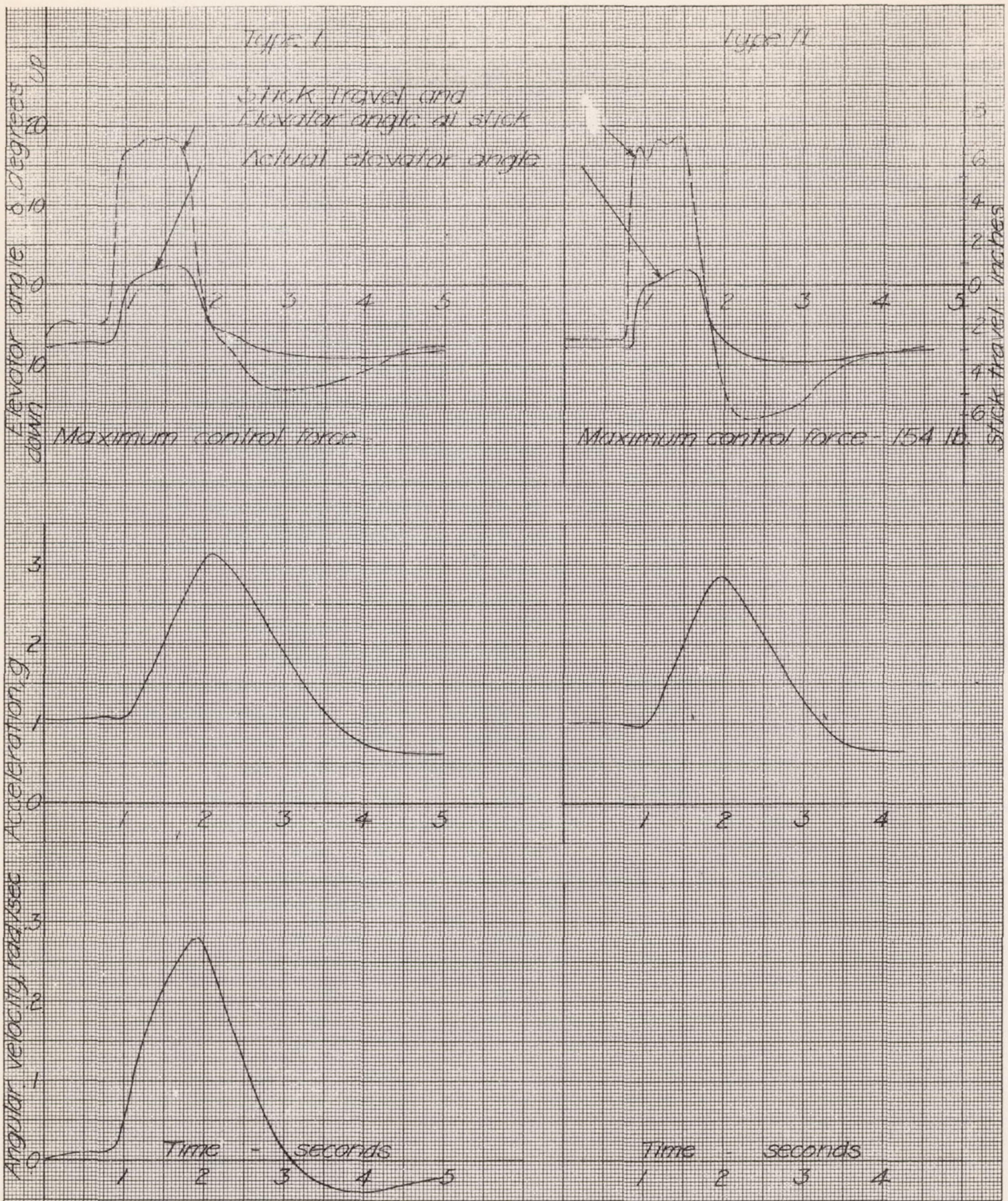

Figure 19 - Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30% MAC, initial airspeed - 201 mph.(ind.)

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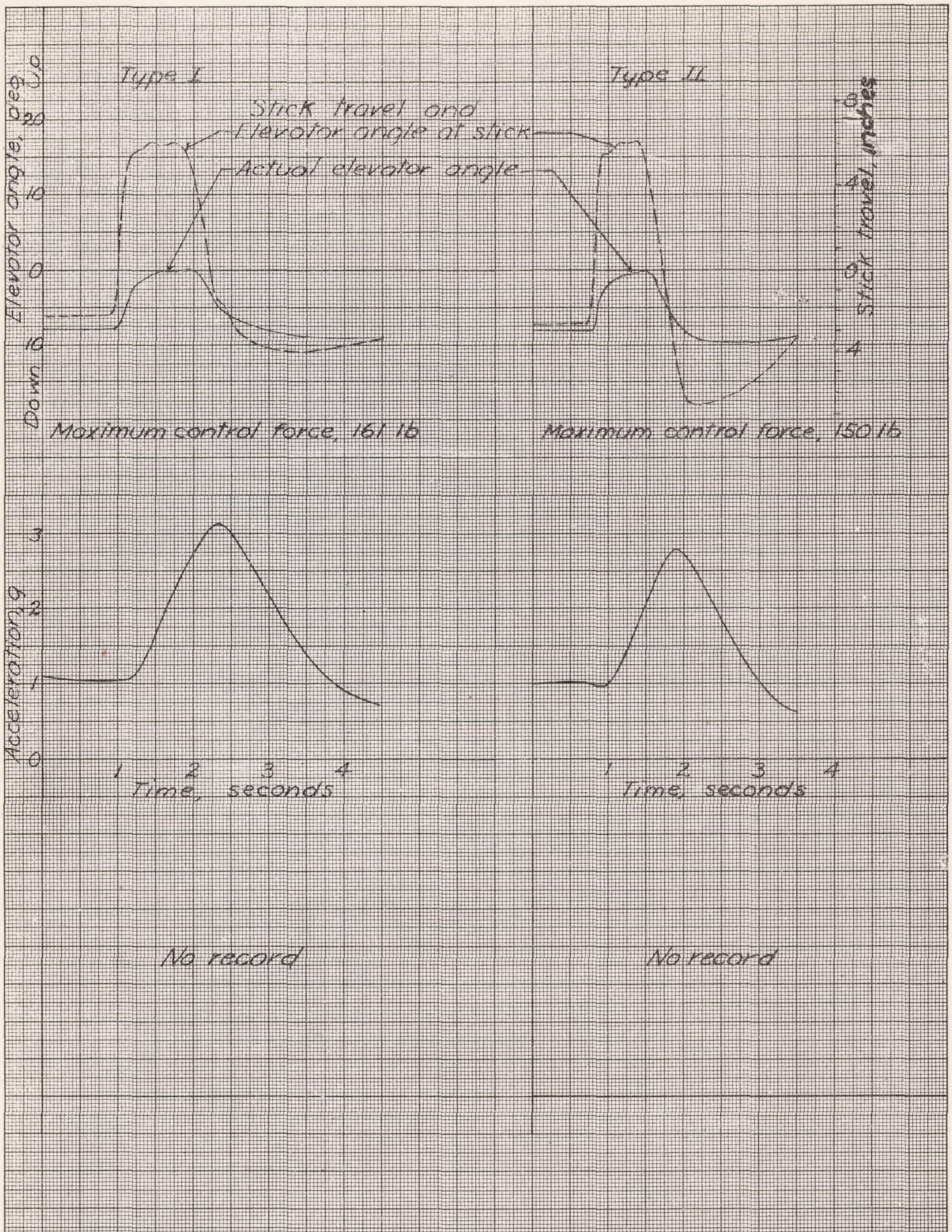

Figure 20.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30 % MAC Initial airspeed - 219 mph (ind.)

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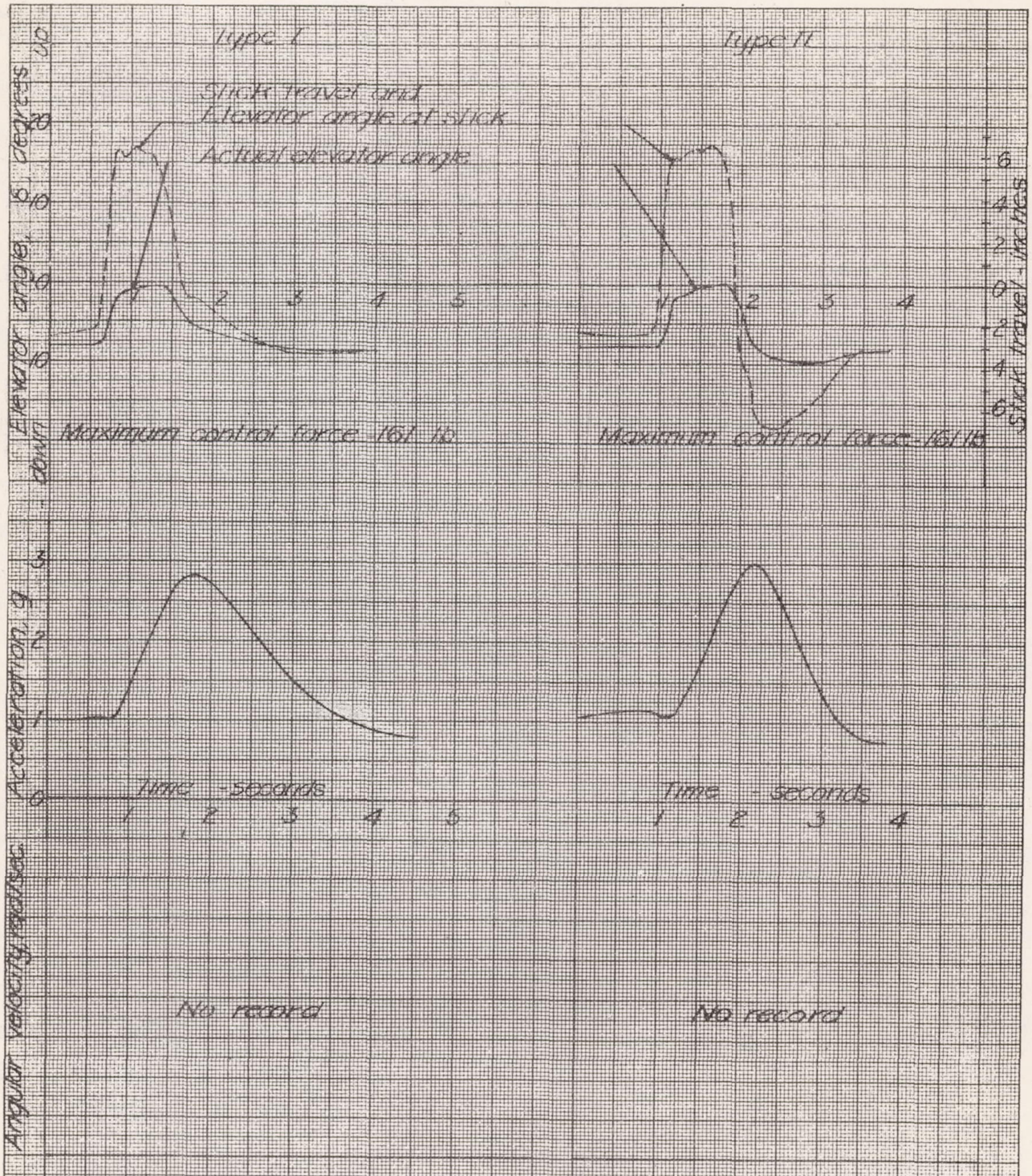

Figure 21.- Variations of measured quantities obtained on the PBM-3 airplane for two types of pull-ups. c.g. at 30% MAC, initial airspeed 219 mph (ind.)

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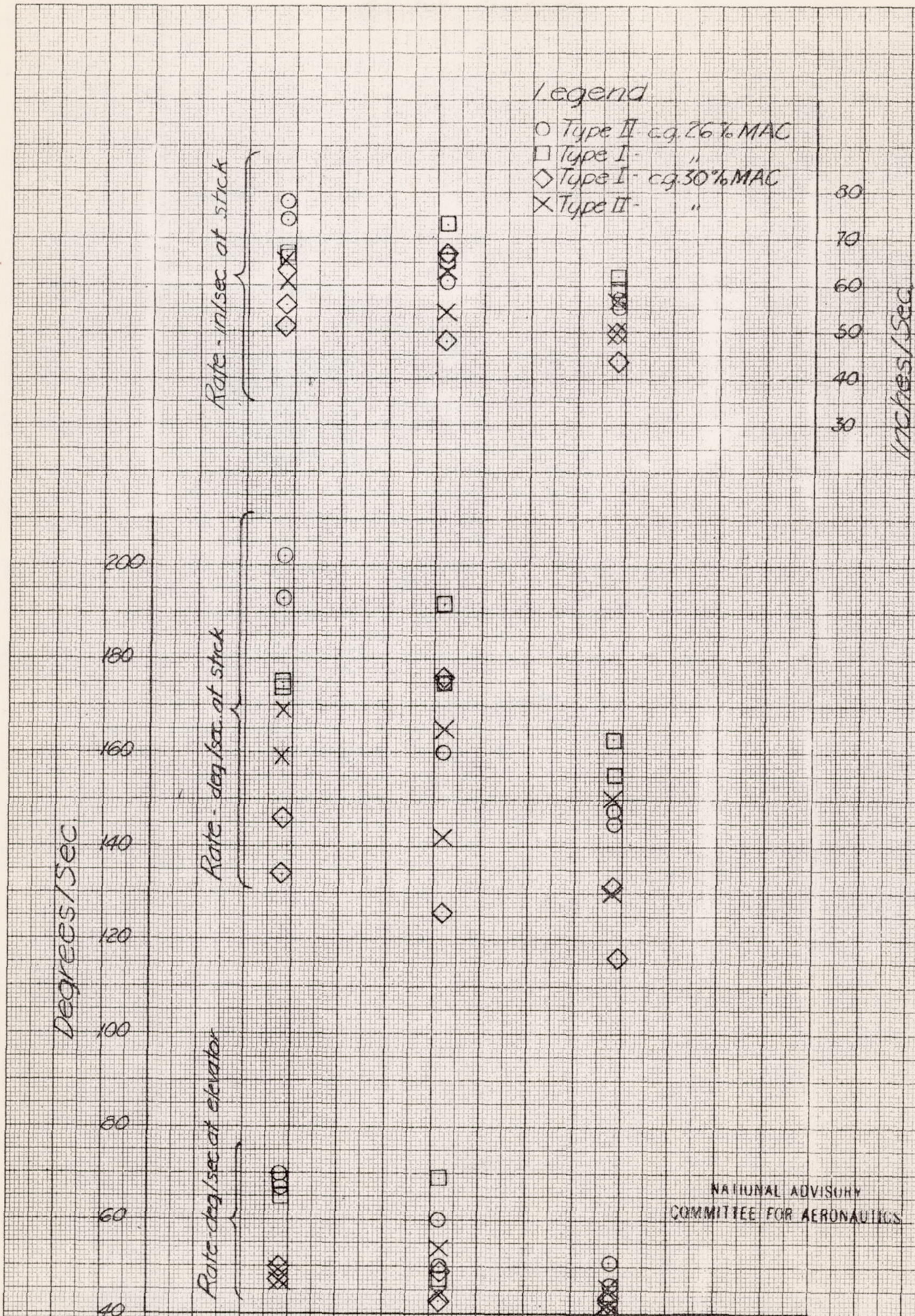

Figure 22-Variation of maximum rates of elevator and stick movement with airspeed for the PBM-3.

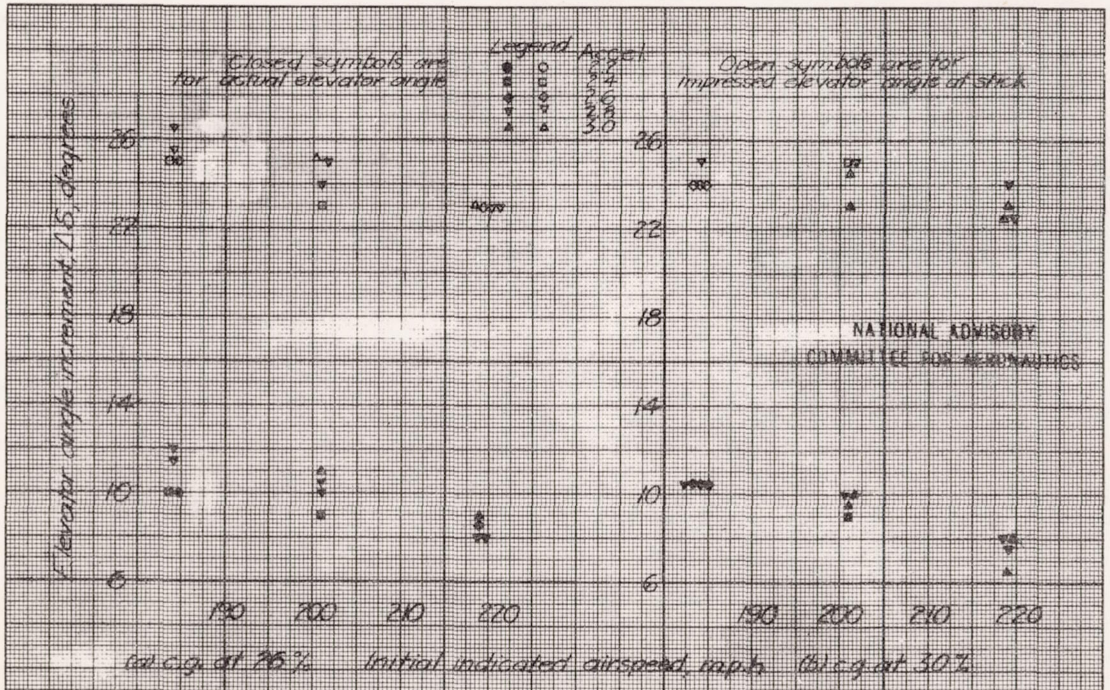

Figure 23-Variation of elevator angle increment with initial airspeed and load factor for the PBM-3.