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NACA

RESEARCH MEMORANDUM

for the

Bureau of Aeronautics, Navy Department

FLIGHT CHARACTERISTICS OF A 1/4-SCALE MODEL OF THE XFV-1 AIRPLANE

(TED NO. NACA DE-378)

By Mark W. Kelly and Louis H. Smaus

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Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

October 15, 1952

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SUMMARY

A 1/4-scale dynamically similar model of the XFV-1 airplane has been flown in the Ames 40- by 80-foot wind tunnel, using the trailing-flight-cable technique. This investigation was devoted to establishing the flight characteristics of the model in forward flight from hovering to wing stall, and in yawed flight (wing span alined with the relative wind) from hovering to the maximum speed at which controlled flight could be maintained. Landings, take-offs, and hovering characteristics in flights close to the ground were also investigated. Since the remote control system for the model was rather complicated and provided artificial damping about the pitch, roll, and yaw axes, sufficient data from the control-system calibration tests are included in this report to specify the performance of the control system in relation to both the model flight tests and the design of an automatic control system for the full-scale airplane.

The model in hovering flight appeared to be neutrally stable. The response of the model to the controls was very rapid, and it was always necessary to provide some amount of artificial damping to maintain control.

The model could be landed with little difficulty by hovering approximately a foot above the floor and then cutting the power. Take-offs were more difficult to perform, primarily because the rate of change in power to the model motors was limited by the characteristics of the available power source.

The model was capable of controlled yawed flight at translational velocities up to and including 20 feet per second. The effectiveness

of the controls decreased with increasing speed, however, and at 25 fps control in pitch, and probably roll, was lost completely.

The model was flown in controlled forward flight from hovering up to 70 fps. During these flights the model appeared to be more difficult to control in yaw than it was in pitch or roll.

The flights of the model were recorded by motion picture cameras. These motion pictures are available on loan from NACA Headquarters as a film supplement to this report.

INTRODUCTION

The XFV-1 convoy-fighter airplane is to be powered by an Allison T-40 gas turbine engine driving a six-bladed counter-rotating Curtiss propeller of special design. This combination will give the airplane a thrust-weight ratio greater than 1, enabling it to hover and take off and land vertically. Control will be maintained in hovering flight by the action of the propeller slipstream on the interdigitated-cruciform tail on which all the movable control surfaces and the landing gear are located. In addition to vertical take-offs, landings, and hovering, the airplane is to be capable of constant altitude controlled forward flight in the speed range from hovering up through the normal flight speeds, and constant altitude yawed flight (wing span alined with the relative wind) from hovering up to 60 fps.

In view of the new and unusual low-speed operational requirements for the XFV-1 and the lack of information on the stability and control parameters associated with the low-speed and hovering phases of the flight range, it appeared desirable to study the behavior of a dynamically similar free-flight model in situations simulating as closely as possible those which will be encountered by the airplane. Considerations of wind-tunnel size, available power and control equipment, and instrumentation problems led to the selection of a 1/4-scale model and the adoption of the trailing-flight-cable technique.

In general, the free-flight tests of the 1/4-scale model which were made in the Ames 40- by 80-foot wind tunnel were performed with the following objectives in mind: first, to demonstrate that the model was capable of successfully performing the operational requirements specified for the airplane; second, to verify and supplement predictions of the stability and controllability of the airplane which were deduced from force tests of a 1/10-scale powered model; and third, to provide information on the new piloting techniques involved in accomplishing transition from normal flight to hovering flight, hovering, and vertical landings and take-offs. These tests were for the most part exploratory in nature, since it was felt that no detailed investigation of any one particular phase of the tests was warranted until qualitative information had been attained for all types of flight being considered.

This investigation consisted of hovering flights at both high and low altitudes, landings and take-offs, yawed flights at various speeds up to 25 fps, forward flights at various speeds up to 70 fps, and forward flights during which the forward speed was changed continuously from 60 fps to less than 10 fps. These flights were recorded in motion pictures, and an abridged copy of these films is available on loan from NACA Headquarters as a film supplement to this report. The discussion of the general flight behavior of the model presented in this report is based upon examination of the motion pictures, and pilots' and observers' impressions of the flights.

Have film

NOMENCLATURE

The unusual nature of the low-speed operation of the XFV-1 has given rise to several terms not commonly encountered. Those that are used in this report are as follows:

Hovering: The flight condition in which the longitudinal axis of the airplane is vertical and in which the propeller is supporting the airplane.

Translation: Movement of the airplane in a horizontal plane at constant speed below the power-off stalling speed.

Yaw translation: Translation in which the wing is alined spanwise with the relative wind.

Pitch translation: Translation in which the plane of symmetry is alined with the relative wind.

Normal flight: All flight at speeds above the power-off stalling speed.

Transition: The change from normal flight to hovering and vice versa.

MODEL DESCRIPTION

A three-view drawing and the important aerodynamic dimensions of the model are presented in figure 1. A tabulation of the major physical data for the full-scale airplane is given in table I. The gross weight of the model for most of the flights was about 250 pounds. This does not include the weight of the trailing flight cable supported by the model which amounted to 1/2 pound per foot of altitude.

Control System

Control of the model was obtained by the remote operation of movable control surfaces located on each of the four tail fins. (See fig. 1.) The function of the model control system was to transfer the pilot's control signals from his controller on the ground to corresponding deflections of these control surfaces on the model. In addition to this, the control system included means for providing the model with artificial damping about the pitch, roll, and yaw axes.

A four-channel (one for each control surface) electro-mechanical servo system was used to convert signals from the pilot and the motion sensing elements of the artificial damping system into the proper control-surface deflections. A simplified block diagram of the control system showing one channel of the servo system and the pitch axis portion of the artificial damping system is given in figure 2. The corresponding signal circuit is shown in figure 3. An electrical signal is fed from the pilot's controller to the servo system (amplifier, actuator, and follow-up pickoff for each channel) which in turn causes a corresponding control-surface deflection (δ). As the model begins to respond to the deflected controls, its angular velocity ($\dot{\theta}$ in this case) is measured by a rate gyro and a signal proportional to this angular motion is fed back to the amplifier to provide the desired additional damping.

The pilot's controller was equipped with a conventional stick for pitch and roll, and a rudder bar for yaw. A separate calibrated roll-control unit was also provided for independent control of the model in roll when desired.

The motion sensing elements of the artificial damping system consisted of three rate gyros orientated about the pitch, roll, and yaw axes and equipped with variable reluctance pickoffs. The gimbal of each gyro was torsionally mounted to provide spring restraint without bearing friction. Damping for the gyro was supplied by an arbitrary amount of silicone fluid placed in the very small air gap of the pickoff.

The servo actuator consisted of a relatively constant-speed electric motor of 1/20 horsepower continuously driving four pairs of counter-rotating magnetic-powder clutches through a worm gear arrangement. Each control surface was attached to an output shaft which was common to one pair of clutches. One or the other of the pair of clutches was energized by a signal from the amplifier, depending on the polarity of the signal. In order to damp out small high-frequency oscillations of the actuator, it was found necessary to install piston-type hydraulic dampers on the linkages connecting the control surfaces to the actuators.

Power Plant

The model power was provided by two 450-volt three-phase, four-pole squirrel-cage induction motors rated at 38 hp each at 11,000 revolutions per minute. These motors were coupled to the propellers through a gear box providing a 5:1 speed reduction. Since the propeller pitch was not adjustable in flight, it was necessary to provide the model motors with variable-frequency power to obtain control of propeller speed. This power was furnished by an auxiliary motor-generator set in the 40- by 80-foot wind tunnel rated at 800 hp at 400 cycles per second. Large-scale changes in power from this motor-generator set were made with the existing control system. In order to provide for the small and relatively rapid power changes which, it was felt, would be necessary to maintain control of the model, a hand-operated rheostat (referred to hereafter as the throttle) was provided. This device was capable of producing a maximum frequency change of about ±20 cps at a maximum rate of about 16 cps per second. Electric power and cooling water were transmitted to the model through the trailing flight cable shown in figure 4.

TEST EQUIPMENT AND TECHNIQUE

Model Tethering

In order to provide some means of saving the model in the event of a power or control-system failure, it was necessary to provide three lines to the model in addition to the flight cable. One of these lines was attached to the nose boom which was attached to the propeller spinner by means of a universal joint. This nose line at the model end was 1/8-inch-stainless-steel aircraft cable. This cable was led to the tunnel ceiling and through a system of pulleys to a shock absorber. A 1-inch manila line was attached to the shock absorber and was led down to a motor-driven winch on the floor. Two men were stationed at the winch to control the amount of slack in the nose line. In addition to the nose line, one tethering line was provided at each wing tip. These were attached to the model on steel tubes which were fastened to the wing-tip armament pods as shown in figure 4. These tubes had been found necessary in flights at the Lockheed plant in order that the wing-tip lines would not be attached aft of the model center of gravity. For all of the hovering and yaw-translation flights the wing-tip lines were 3/16-inch sash cord. For most of the pitch-translation flights this was replaced with 1/4-inch manila line. The wing-tip lines were led from the model through two eyebolts in the floor about 20 feet on either side of the model. They were then fastened to a length of 1-inch manila line which was held manually to provide slack or restraint, as required.

The flight cable mentioned previously carried all the control-system and instrument leads in addition to the model motor power and coolant lines. This cable was by far the heaviest line attached to the model (approximately 1/2 pound per foot) and to minimize its effect upon the stability of the model was attached to the model as near to the center-of-gravity location as possible. For most of the hovering flights the flight cable was attached to the model as shown in figure 4. In order to avoid interference between the flight cable and the model tail when the model was flown in pitch translation at the higher speeds (lower angles of attack), the flight cord was wrapped around the fuselage and fastened to the bottom of the fuselage directly under the previously used attachment point on the pilot's canopy.

Instrumentation

The flight characteristics of the model were recorded by motion picture cameras. Control-surface deflections and controller input signals were recorded continuously on a multichannel oscillograph. These records were taken primarily to provide a running check on the performance of the control system. Power and current inputs to the model motors were recorded continuously on recording meters. Wind-tunnel speed, model-motor speed and temperatures, and control-surface deflections were recorded continuously by a 35 millimeter camera.

Test Setup for Hovering, Yaw-Translation, and Low-Speed Pitch-Translation Flights

Most of the hovering and low-speed translation flights were performed in the return section of the wind tunnel just in front of the contraction cone. The test setup for the low-speed pitch-translation flights is shown in figure 5. It was found necessary to orientate the pilot with respect to the model so that his response on the controls to the motions of the model was as natural as possible. For the hovering flights the pilot was in approximately the same position relative to the model as that used for the pitch-translation flights, and this location was satisfactory. However, for the yaw-translation flights the pilot remained in the same location as that shown in figure 5, while the model was rotated 90° to aline the wing with the tunnel air stream. This was done to expedite the tests although it made the pilot's task of properly interpreting and responding to the motions of the model considerably more difficult.

Test Setup for High-Speed Translation Flights

All the translation flights at speeds greater than 30 fps were made with the model in the test section as shown in figure 6. Except for the wing-tip tether man and an assistant, the test crew was stationed outside the wind tunnel. It was originally intended that all of the test crew be stationed outside the tunnel, and the first wing-tip tethering system employed had the wing-tip lines from the model fastened directly to the tunnel floor and ceiling through lengths of bungee. However, it was found that this did not allow the model enough freedom of movement, and this system was abandoned in favor of the manual control of the wing-tip lines which had been used for the hovering flights.

FLIGHT TESTS

Hovering and Low-Speed Flights

Division of controls.- On the first hovering flights, the model pilot controlled only pitch and yaw. Roll control was performed independently by another operator. The throttle on these first flights was operated by the same person who manned the main power control panel for the motor-generator set. As the test crew became more familiar with their tasks and as the pilot gained proficiency, first roll control and then flight power control was given to the pilot.

Test procedure.- The test procedure followed during the hovering flights was as follows. With the model on the tunnel floor, partial power was applied to the motors to aid the men at the winch in hoisting the model. The model was then hoisted to some predetermined altitude (usually 2 or 3 feet) and the nose line was secured to a cleat on the tunnel floor. This was done so that the model could not drop to the floor from a high altitude in case the men at the winch lost control of the nose line. The model was then hoisted to the flight altitude and the wing-tip tethering lines were pulled taut. Power to provide excess thrust was applied by the main power controller while the pilot's throttle was set for full power. The nose line was slacked off until the nose boom was about 45° from the vertical. Power was then reduced with the throttle until the model lost altitude slightly and flew away from the wing-tip tethers. The flights were started from taut wing-tip lines rather than from a taut nose line because the model was more controllable when pulling against the wing-tip lines than it was when hanging from the nose line. The flight was terminated by pulling both the wing-tip and nose lines taut simultaneously. Power was then reduced and the model was lowered to the floor with the winch.

The first attempts at landing were made by maneuvering the model to an altitude of about 1 or 2 feet and then suddenly reducing the power as far as possible with the throttle. However, the power reduction obtained in this manner was not enough to keep the model securely on the ground after the initial contact. On all of these attempts the model bounced and skipped along the floor out of control until restrained by the tethering lines. Successful landings were made by having the main power-control operator open the main breakers to the model motors as the model began to drop to the floor after the pilot had reduced power to land.

Power control during take-offs was also difficult and the operation was performed as follows. With the model on the ground and the nose line slack, power was advanced by the operator at the main power panel while the pilot held his throttle in the full low power position. When the power had been advanced to a point just below that required for flight, the pilot took over and rapidly advanced the power to the take-off rating. This had to be carefully done in order that the power increase was rapid enough to quickly provide satisfactory control of the model and still was slow enough to keep the rate of power increase below that which would open the overload circuit breakers on the motor-generator set.

The low-speed pitch and yaw translation flights which were made in the return passage were performed in the same manner as were the hovering flights. For the pitch-translation flights at free-stream velocities of over 20 feet per second, it was necessary to remove the wing-tip lines from the eyebolts in the floor and have them held by men stationed upstream of the model. This was necessary because the model was held approximately in the hovering attitude by the tethering system and therefore had very large drag forces when tethered.

High-Speed Pitch-Translation Flights

Scope.- The pitch-translation flights performed in the test section covered a range of speeds from 20 fps to 70 fps. In addition, two flights were made in which the tunnel speed was decreased continuously from 60 fps to 0 fps. The model was flown both with and without leading-edge slats. On these flights the pilot operated all of the model flight controls.

Test procedure.- The test procedure followed for the high-speed pitch-translation flights was much the same as that used for the hovering and low-speed translation flights in the return section. The main difference was in the application of the model power. Instead of beginning these flights with excess power and then having the pilot reduce power to that required for trim, the pilot held his throttle in a neutral position and the main power-control operator set the power to that required for flight at that particular speed. When this had been done the pilot took over the power control, the tethering lines were relaxed, and the flight was begun. This procedure was necessary at each flight speed because the variation in power required for flight over the speed range tested was larger than the range of power available from the throttle. When the transition flights were made, it was necessary for the pilot and the main power-control operator to coordinate their efforts, the pilot calling for a change in power setting as he approached the limit of his power control, and then controlling the model power while the coarse change was being made at the main power-control panel.

In general, the flights in the test section were much more difficult to perform than the flights in the return section. This was primarily due to the large reduction in available flight area which made it necessary to maneuver the model much more precisely than had previously been required. The men on the tethering lines had to be particularly careful at the higher tunnel speeds when the model at times had a tendency to oscillate when the tethers were taut. Also, the field of vision of the flight area by all the crew except the wing-tip tether man was somewhat restricted since they were outside the tunnel and had to watch the model through windows.

CONTROL-SYSTEM TESTS AND CHARACTERISTICS

The model behavior is determined not only by its aerodynamic characteristics but also by the control-system characteristics, especially as they affect the over-all damping of the model. Therefore, in interpreting the model test results, it is necessary to consider the control-system behavior. It is also desirable to know the extent to which the characteristics of the automatic stabilization system can be realized by present-day equipment in the full-scale airplane. Therefore, tests were made to determine quantitatively the performance of the control system. The characteristics which need to be known to permit adequate analysis of the system are the gearings, or sensitivities, and the dynamic responses of the servo system and of the rate gyros.

For convenience in the following presentation the four servo channels are referred to by number as follows: The control surface of the upper left fin when viewed from the airplane nose is driven by servo channel number 1, that of the lower left fin by number 2, that of the lower right fin by number 3, and that of the upper right fin by number 4.

Steady-State Characteristics

Amplifier.- Examination and preliminary tests indicated that the amplifier exhibited nonlinear characteristics well before other components in the system and, hence, was the limiting element insofar as linearity was concerned. The static gain of the amplifier for various input voltage levels is given in figure 7. Amplifier gain control setting was the same as used in flight and bench tests. It can be seen that the output is linear only up to an input of 0.1 volt although the biggest change in slope of the curve occurs somewhat beyond 0.2 volt. The amplifier is effectively saturated at 0.6 volt.

Over-all gearing of rate-gyro servo-system combination.- The over-all gearing is given in terms of the control-surface deflection per unit angular velocity input to the rate gyro. All data were taken with a rate potentiometer setting of 4 and a servo feedback potentiometer setting of 5 as normally used in flight. The deflection of control-surface number 2 was measured in each case. Graphs of the gearings are given in figure 8. The curved portions at the extremes of the pitch gearing plot are due to the characteristics of the servo follow-up pickoff at large deflection angles.

The slopes of the lines represent the over-all gearings and are as follows:

Roll	23° per radian per second
Pitch	72° per radian per second
Yaw	29° per radian per second

Rate-gyro sensitivity.- The sensitivities of the gyros and potentiometers for the normally used setting of 4 are as follows:

	Gyro sensitivity (volts/rad/sec)	Transmission of rate potentiometer (percent of input)	Combined rate sensitivity (volts/rad/sec)
Roll	10.6	22.6 percent	2.40
Pitch	16.0	42.0 percent	6.72
Yaw	11.6	23.5 percent	2.73

The rate-gyro output was found to be linear up to 6 volts or more. The rate potentiometers were found to be quite nonlinear and graphs of their calibrations are given in figure 9 so that attenuations for settings other than 4 may be obtained.

Servo-system static sensitivity.- The sensitivity of the servo system alone was calculated from the foregoing data for channel 2 at a feedback setting of 5. The average value obtained was 10° deflection per volt input to the amplifier. During flight tests all servo channels were set to give this same sensitivity.

Dynamic Characteristics

Rate gyros.- The undamped natural frequency of the rate gyros was 59 cps. Damping of the gyros was variable and the transient responses of the pitch gyro for three conditions are given in figure 10. The curve labeled light damping represents the condition of the gyro that existed at the conclusion of the tests in the return section of the tunnel. The rise time, defined as the time required to reach a magnitude within 10 percent of the final value, is about 0.01 second. The normal damping curve shows a rise time of 0.05 second which was the value existing at the start of the flight tests in the test section of the tunnel.

Tests of the yaw and roll gyros showed them to have rise times on the order of 0.03 to 0.05 second.

Variations in the responses due to different amplitudes of input steps were found to be no more than those occurring during repeated steps at the same amplitude.

It is probable that the value of damping decreased somewhat throughout the flight tests due to the nature of the damping mechanism employed. While possibly significant during the return-section tests since these occupied a long period of time, the change during test-section flights was very likely negligible.

Although rise times of 0.03 to 0.05 second are not considered excessive compared to the response times of the model, it would appear desirable in future tests to reduce the damping of all gyros to give a rise time of about 0.02 second. Improved phase response, that is, less phase lag at low frequencies, would thus be obtained.

Servo-system transient tests.- The response of the servo system to a step input voltage was obtained for various input magnitudes. The tests were made without hinge-moment load on the control surfaces; under load the responses would probably be damped a little more but would have slightly longer rise times. This effect should be negligible since the air loads were small compared to the mechanical loads of the system.

As mentioned previously, an input of 0.1 volt or less was required to maintain completely linear operation. However, this value would not produce a usable output and 0.2 volt was considered the lowest practical amplitude. A level of 0.5 volt was probably characteristic of normal operation since the amplifier did not entirely saturate at this value.

It should be noted that the input voltage to the servo system exists as an effective error voltage (net input to the amplifier) only at the start of the transient; as soon as the output responds, the voltage from the follow-up pickoff begins to cancel the input voltage, thereby reducing the error voltage. Hence, the amplifier may only operate in the nonlinear range for a very short time depending, of course, on the actual input magnitude.

Transient responses for channel 1 of the system at a feedback setting of 5 and the amplifier gain near maximum, which were the values used for flight tests, are presented in figure 11. The rise time from start of the step input varies between 0.04 and 0.09 second and was about 0.07 second for the majority of responses.

There is considerable variation between the responses in the two directions and for different amplitudes. The response for any one condition could be repeated quite consistently, however. Friction in the system and unequal amounts of fluid in the servo hydraulic dampers are likely causes of these differences. The small offsets in the curves are believed due to small variations in the contact resistance of the recording potentiometer since very small angles were being measured.

For the sake of comparison, the responses of channel 1 and of two other servo channels for a step input of 0.5 volt, other conditions being the same, are given in figure 12. The two directions of motion are illustrated for each channel. The sharp spikes on the curves for servo number 4 appear to be due to irregularities in the recording potentiometer.

<u>Servo-system frequency response</u>.- The amplitude ratio of the frequency response of channel 2 of the servo system as determined from sine-wave tests is shown by the solid line in figure 13. Input magnitude was ± 0.5 volt with feedback potentiometer set at 5. For comparison and to supplement the sine-wave tests, several frequency responses were calculated from transient responses to a step input with the aid of an IBM machine and are also shown in figure 13. The dash-dot curve is for the same condition as the response obtained from sine-wave tests. The other two curves represent some extremes of operation encountered during the tests.

Since the system is operating in the nonlinear range a part of the time, it would be expected that there would be differences in the frequency responses obtained in the two manners. The peak value of input for a sine-wave test is constant with frequency, while the amplitudes of the frequency components of a step function input vary inversely with frequency.

RESULTS AND DISCUSSION

The main results of the tests are discussed in the following paragraphs. However, the flight characteristics of the model are more clearly illustrated in the motion picture records than is possible in a written description. For this reason, a film supplement to this report has been prepared and is available on loan from NACA Headquarters.

In analyzing the flight behavior of the model, it is important that the limitations inherent in a test of this type be kept in mind. One of the most serious of these is the fact that the model pilot has no feel of the accelerations of the model and must wait until an attitude change has occurred before taking corrective action. Thus, there is a time delay in the model-pilot dynamic system that is not encountered in the airplane-pilot dynamic system. Also, as shown by the dynamic similarity relationships given in the appendix, the time scale of the model is equal to that of the airplane multiplied by the square root of the model scale, while the response of the pilot is independent of scale. Hence, even neglecting the lack of feel mentioned previously, the pilot's response compared to the model characteristics is one-half as fast as it would be when compared with those for the full-scale airplane. These limitations would apply to remote controlled flights of any dynamically similar model.

In order to minimize the interaction between the model and its flight cable and tethering lines, all the tethering lines attached to the model during these flights were as small as possible. The flight cable (the largest of the lines) was attached close to the model center of gravity. With this arrangement, it is believed that when the model was in steady-state flight or undergoing maneuvers of a small magnitude the effect of these external lines upon the model flight behavior was small.

Hovering.- The hovering flights were directed particularly at the following objectives: first, familiarization of the test crew with their tasks and with the model; second, evaluating roughly the amount of artificial damping from the rate gyros necessary to give the model stability and control characteristics which were satisfactory to the pilot; and third, investigation of the behavior of the model when flown at the low altitudes required in take-off and landing operations.

It was found that the control surfaces in the slipstream were very effective when the model was hovering with the tail a foot or more above the floor. In fact, the response of the model to the controls and to random disturbances was so rapid that it was always necessary to provide some amount of artificial damping in order to slow down the angular velocities to values consistent with the pilot's response time.

In the time available for the tests, it was not possible to determine an optimum combination of damping about the pitch, roll, and yaw axes (i.e., the minimum total amount of rate-gyro signal to provide satisfactory stability and controllability). The first hovering flight was made with a relatively large amount of damping and, while the flight was smooth and steady, the pilot complained of lack of maneuverability, since the controller signal was small with respect to the damping signal. It was not possible to readily increase the controller outputs above the values being used, so the damping signal setting on subsequent flights was reduced equal amounts on all axes until a balance between stability and controllability satisfactory to the pilot had been achieved. The final damping signal settled upon was a rate setting of 4.0 to all gyros which gave a control-surface output of about 70° per radian per second in pitch and 25° per radian per second in roll and yaw. However, these amounts of damping are by no means the minimum required for controlled flight of the model and represent only the results of a brief investigation. One flight was made with no damping in yaw and two flights were made with no damping in pitch due to failures in the rate-gyro circuits. On all of these flights the pilot was able to maintain control after he became used to the increased sensitivity of the model, although there was a tendency to over-control resulting in some oscillations about the undamped axis. Early in the tests two attempts were made to fly the model with no damping whatsoever, but on each try control was quickly lost. It is possible that by increasing the ratio of stick motion to control-surface deflection and gradually eliminating the artificial damping on one axis at a time the model could be flown with no artificial damping at all. However, it would not appear that the model could be flown easily by one pilot under these conditions.

No difficulty was encountered with altitude control during the hovering flights although the speed response of the motor-generator set was not as high as had been desired. It was found that control of altitude and rate of change of altitude were best made by making small and careful power adjustments and allowing time for the model to respond. It should be noted that some amount of altitude stability was obtained from the flight cord, since the weight of this line which was carried by the model was a direct function of altitude (approximately 1/2 pound per foot).

The model was very difficult to control when the tail surfaces were within 1 foot of the ground and controlled flights at altitudes less than 1 foot were never maintained for any appreciable length of time. This control difficulty was shown by tuft studies to be due to the deflection of the slipstream by the floor so that the direction of the resultant velocity over the control surfaces was roughly parallel to the hinge lines.

Landings.- Landings were fairly easy to perform by hovering the model between 1 and 2 feet from the floor and then cutting the power to rapidly descend through the region of low control effectiveness. In addition to avoiding flight at too low an altitude on the landing approach, it was also necessary for the pilot to keep the longitudinal axis of the model vertical and to avoid high translatory velocities when contact with the floor was made. On one landing in which the pilot was attempting to hit a target on the floor, rudder was applied in order to move closer to the target just as the power was cut. The model landed on two wheels and would have fallen except for the nose line. However, this was the only instance encountered during the investigation in which the model threatened to topple during a landing. In general, the pilot had little difficulty in maintaining the attitude required for a safe landing.

Take-offs.- It was found more difficult to perform smooth take-offs with the model than smooth landings. This was due mainly to the previously mentioned limited rate of power response from the motor-generator set. Another difficulty encountered was the tendency of the model to roll backward on the floor as the power was advanced. This was caused by the lifting force of the slipstream on the wings, which are set at positive incidence. This ground roll was eliminated on the model flights by setting the model to the side of the flight area so that the lift of the wings could be taken out on the wing-tip tethering lines. Take-offs were accomplished in this manner but they were never very smooth, and were characterized by erratic and sometimes large translational velocities until the model had risen away from the region of poor control near the ground. It should be noted here that the time spent on the take-off investigation was very limited and, had the pilot been given more practice, the flights would have undoubtedly been smoother.

Yaw translation.- The number of flights devoted to yaw translation was limited to four, and these were devoted primarily to bracketing the yaw translation speed at which control would be lost. It was demonstrated that the controls were still effective at a yaw translation speed of 20 fps, but at 25 fps control was lost in pitch, and possibly roll. Due to this loss of control the time spent in free flight at 25 fps away from the tethering lines was very limited. It was sufficient, however, to show that the model would respond to yaw control inputs and had no response, for all practical purposes, in pitch and roll. This loss of control in yaw translation between speeds of 20 fps and 25 fps is somewhat lower than the control-loss speed of 25 fps to 30 fps predicted from the results of the 1/10-scale-model force tests. However, these predictions were based upon studies of yawing moment required for trim versus yawing moment available from the tail. It appears logical that, with this tail configuration, control would be lost in pitch and roll before it is lost in yaw; since, when the upstream control surfaces are out of the slipstream, the yaw control response of the system is the only one which is not distorted. Under these conditions a pure pitch input signal by the pilot will result in a combination of pitch and roll response from the airplane, and vice-versa, whereas a pure yaw input signal should yield a pure yaw response.

Pitch translation.- Satisfactory control in pitch translation was demonstrated through a range of speeds from 20 fps to 70 fps. The model was flown both with and without leading-edge slats and, while tuft studies indicated that extended leading-edge slats reduced the amount of stalled area on the wing, neither the pilot nor the observers noticed any significant differences in the flight characteristics of the model.

At 70 fps, the highest speed flown in pitch translation, the model was at about 25° angle of attack. The tufts on the wing indicated that the wing outboard of the propeller slipstream was still stalled. However, at this speed the tethering loads were becoming quite large, and the model indicated a tendency to oscillate in pitch when restrained by the tethering lines. In view of these difficulties, it was deemed advisable not to risk the model in flights above this speed. It does not appear that any serious difficulties should be encountered by the full-scale airplane in the flight range between the advent of wing stall and 25° angle of attack.

At the beginning of the test it was expected that one of the worst difficulties encountered in the pitch-translation flights would be in the coordination of angle of attack and model power to hold a steady position in the tunnel. In spite of the low rate of power response available for the test, this problem failed to materialize. Figure 14 presents a power record made during a continuous slow down transition in which the model was flown from 60 fps to less than 10 fps. It is apparent that no large or abrupt changes in power were made even though it was necessary to change the power setting occasionally with the relatively coarse control at the main power panel.

The change in elevator angle required to trim with speed was not as severe as predicted from tests of the 1/10-scale model. This may have been partially due to the change in moment contributed from the flight cable as the model changed attitude and speed.

In general, the motion of the model on these flights was primarily in yaw. On some flights the pilot called for more damping in yaw, and the setting of the rate potentiometer for the yaw rate gyro was increased from 4.0 to 4.5. Controlled flights were made with both settings. At speeds of 65 fps and 70 fps, it appeared that control in pitch was becoming more critical and the tendency to yawing motions was diminishing. However, this may have been caused by random disturbances from the nose line, since this was now at a relatively large angle to the thrust line of the model and hence could contribute sizable pitching moments.

Control system.- Although the transient responses of the control system presented in figures 11 and 12 are somewhat erratic, the net effect on the flight characteristics of the model should be small since the over-all response of the control system is fast compared to the response of the model and pilot. This conclusion is supported by the frequency-response data presented in figure 13, where it is shown that, in the frequency range of interest as far as the model is concerned (up to 1 or 2 cps), the amplitude ratio and phase are both within reasonable limits.

In order to transfer the data obtained from the model-control-system tests into information applicable to the airplane control system, it is necessary to refer to the dynamic similarity relationships outlined in the appendix. Here it is shown that for a 1/4-scale model, full-scale time is twice that at model scale. Therefore, the dynamic requirements for the airplane control system need be only half as stringent as those of the model system; hence, the rise time could be twice that of the model components, or, looking at it in another way, the equivalent natural frequency need be only half that of the model components.

Power at full scale is increased by a factor of the airplane-model-length ratio to the 7/2 power which, in this case, is 128 times. Thus the 1/20 hp servo drive motor on the model represents a total of 6.4 hp at full scale. Assuming that four separate hydraulic servo valves and actuators are used, each would have to handle 1.6 hp, a figure easily obtainable with modern high-performance systems of the required dynamic characteristics. This figure is believed to be very conservative because the gear box on the model servo absorbed most of the load; this was shown by the fact that the motor drew more than rated current with the clutches disengaged.

CONCLUSIONS

The following conclusions pertaining to the general flight behavior of the XFV-1 airplane were made from the results of flight tests of the 1/4-scale model:

1. The airplane in hovering flight will probably appear to be neutrally stable to the pilot. It is possible that the airplane may be controllable without artificial stabilization, but it is questionable whether the handling qualities would be considered good by pilots. It would be desirable to make provision in the prototype airplane for automatic stabilization equivalent to that used on the model. Data are presented for the automatic stabilization system to provide the basis upon which specifications of an autopilot for a full-scale airplane could be made.

2. Landings and take-offs in calm air should not be difficult, provided the pilot has sufficient rate of change of thrust to move the airplane quickly through the region of poor control near the ground. In this regard, the rate of change of thrust available to the model in these tests could not be considered satisfactory for the airplane. Landings and take-offs at constant translational wind velocities were not attempted in this investigation, but they would certainly appear to be more difficult than those done in still air.

3. Flight of the airplane in yaw translation will probably be limited to speeds of 40 fps and under. As the speed is increased, the control effectiveness will steadily diminish and at 50 fps control in pitch and roll will be completely gone.

4. The airplane should be controllable all through the pitch-translation speed range. During this investigation of forward flight, control of the model in yaw was usually more difficult than it was in pitch or roll.

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APPENDIX

CONDITIONS FOR DYNAMIC SIMILARITY

If the effects of Mach number and Reynolds number are not significant, the motions of a model will be similar to those at full scale if the model density and Froude number are the same as the airplane density and Froude number. In other words, if compressibility and viscous effects can be neglected, the dynamic characteristics of the model will be representative of those of the airplane if

Dynamic Similarity Equations

$$\left(\frac{W}{D^3}\right)_{model} = \left(\frac{W}{D^3}\right)_{airplane}$$

and

$$\left(\frac{V^2}{gD}\right)_{model} = \left(\frac{V^2}{gD}\right)_{airplane}$$

These relationships lead to the following requirements between the model and the full-scale airplane:

Quantity	Value at full scale	Value at model scale
Length	D	$d = D(d/D)$
Area	S	$S(d/D)^2$
Volume	V	$V(d/D)^3$
Density	ρ	ρ
Mass	m	$m(d/D)^3$
Force	F	$F(d/D)^3$
Linear acceleration	a, g	a, g
Angular acceleration	α	$\alpha(d/D)^{-1}$
Linear velocity	V	$V(d/D)^{1/2}$
Angular velocity	ω	$\omega(d/D)^{-1/2}$
Time	T	$T(d/D)^{1/2}$
Moment	M	$M(d/D)^4$
Power	P	$P(d/D)^{7/2}$
Dynamic pressure	q	$q(d/D)$

Quantity	Value at full scale	Value at model scale
Blade angle	β	β
Reynolds number	R	$R(d/D)^{3/2}$
Mach number	M	$M(d/D)^{1/2}$
Moment of inertia	I	$I(d/D)^5$
Radius of gyration	k	$k(d/D)$

TABLE I.- FULL-SCALE PHYSICAL PROPERTIES
OF THE XFV-1 AIRPLANE (TAKE-OFF)

Gross weight	15,600
Maximum horsepower	7,000
Propeller revolutions per minute	1,100
Propeller diameter (feet)	16
Activity factor	140
Wing	
Span, feet	27.5
Root chord, feet	13.5
Tip chord, feet	4.417
Mean aerodynamic chord, feet	9.708
Aspect ratio	3.07
Taper ratio	0.327
Area, square feet	246
Dihedral of wing reference plane through 40-percent chord, degrees	5
Incidence, degrees	1
Length of wing-tip armament pods, feet	14
Diameter of wing-tip armament pods, feet	1.5
Airfoil section	NACA 65A206
Tail	
Span, feet	12.255
Root chord, feet	7.083
Tip chord, feet	2.667
Mean aerodynamic chord, feet	5.208
Aspect ratio	3.55
Taper ratio	0.376
Total area of four surfaces, square feet	169.0
Total area of four movable surfaces, square feet	32.8
Incidence (angle in vertical plane) between fuselage reference line and intersection of all chord planes, degrees	-4
Sweepback angle, quarter chord, degrees	30
Airfoil section	NACA 65A007

FIGURE LEGENDS

Figure 1.- Three-view drawing of the 1/4-scale model of the XFV-1 airplane.

Figure 2.- Block diagram of control system.

Figure 3.- Schematic diagram of one channel of control system.

Figure 4.- Photograph of the model with tethering lines and flight cable attached for hovering flight.

Figure 5.- View of the model and test equipment as arranged for the low-speed pitch-translation flights in the return passage of the wind tunnel.

Figure 6.- Sketch of test setup for the high-speed translation flights in the wind-tunnel test section.

Figure 7.- Amplifier gain characteristics.

Figure 8.- Rate gyro - servo gearing calibrations for servo no. 2 with a rate setting of 4.0 and a feedback setting of 5.0.

Figure 9.- Rate potentiometer calibrations.

Figure 10.- Transient response of pitch rate gyro.

Figure 11.- Transient response of servo no. 1 for various step input voltages.

Figure 12.- Transient responses of three servos for 0.5-volt setup-input signal.

Figure 13.- Frequency response of servo system. (a) Amplitude ratio.

Figure 13.- Concluded. (b) Phase.

Figure 14.- Time history of variation in power input to model motors during a slow-down transition from 60 fps to less than 10 fps.

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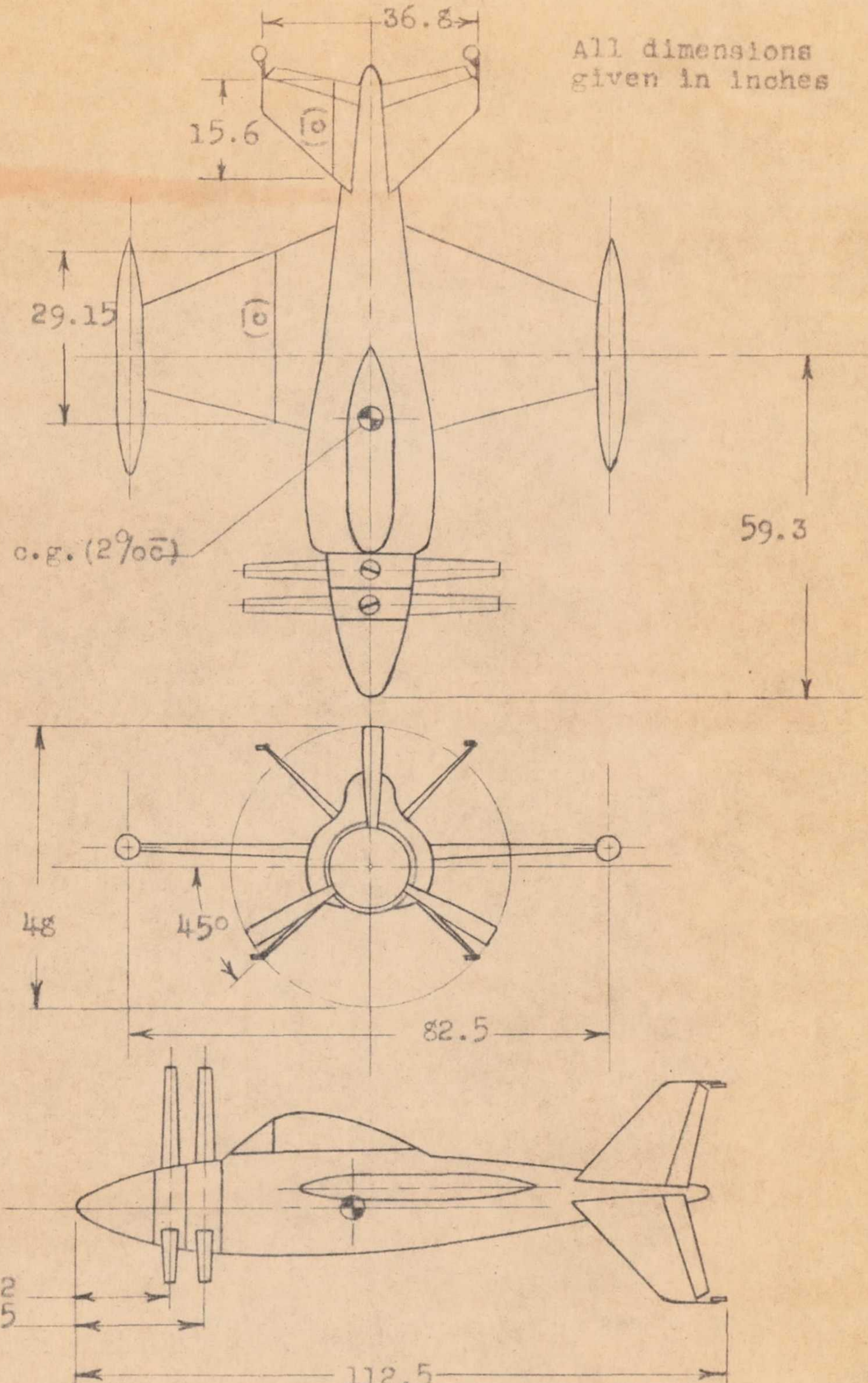

Figure 1.- Three-view drawing of the 1/4-scale model of the XFV-1 airplane.

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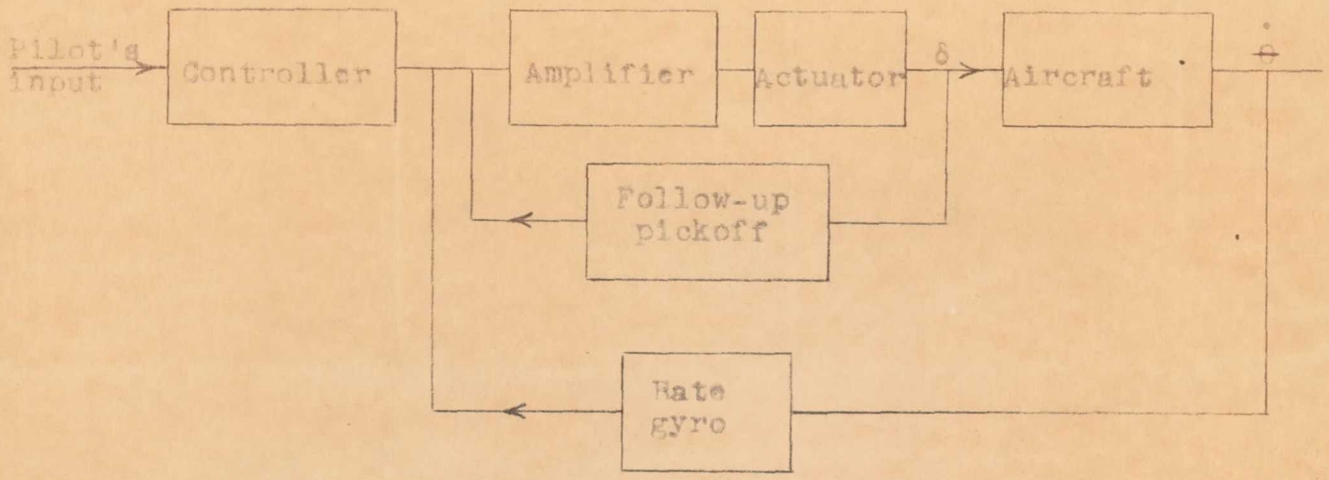

Figure 2.- Block diagram of control system.

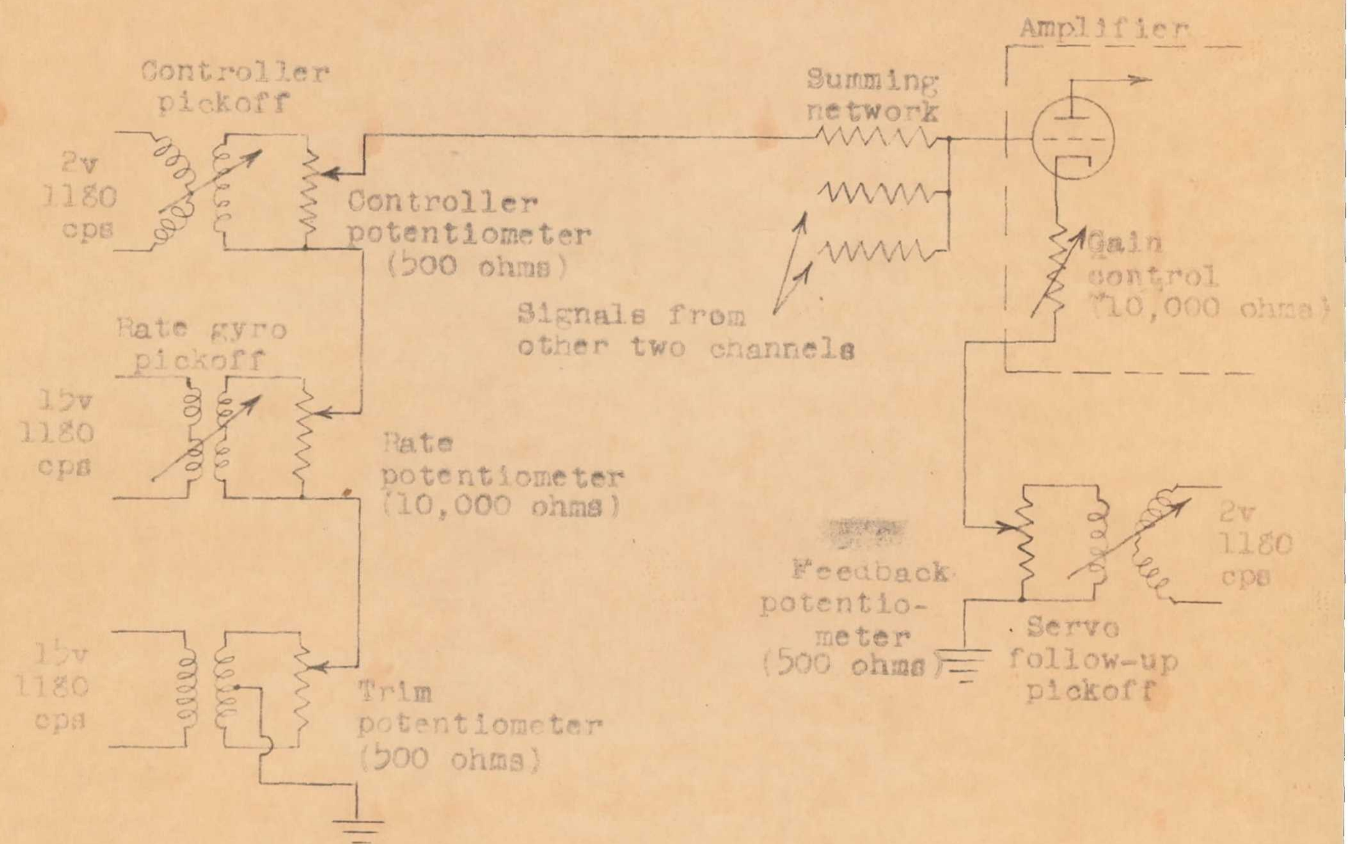

Figure 3.- Schematic diagram of one channel of control system.

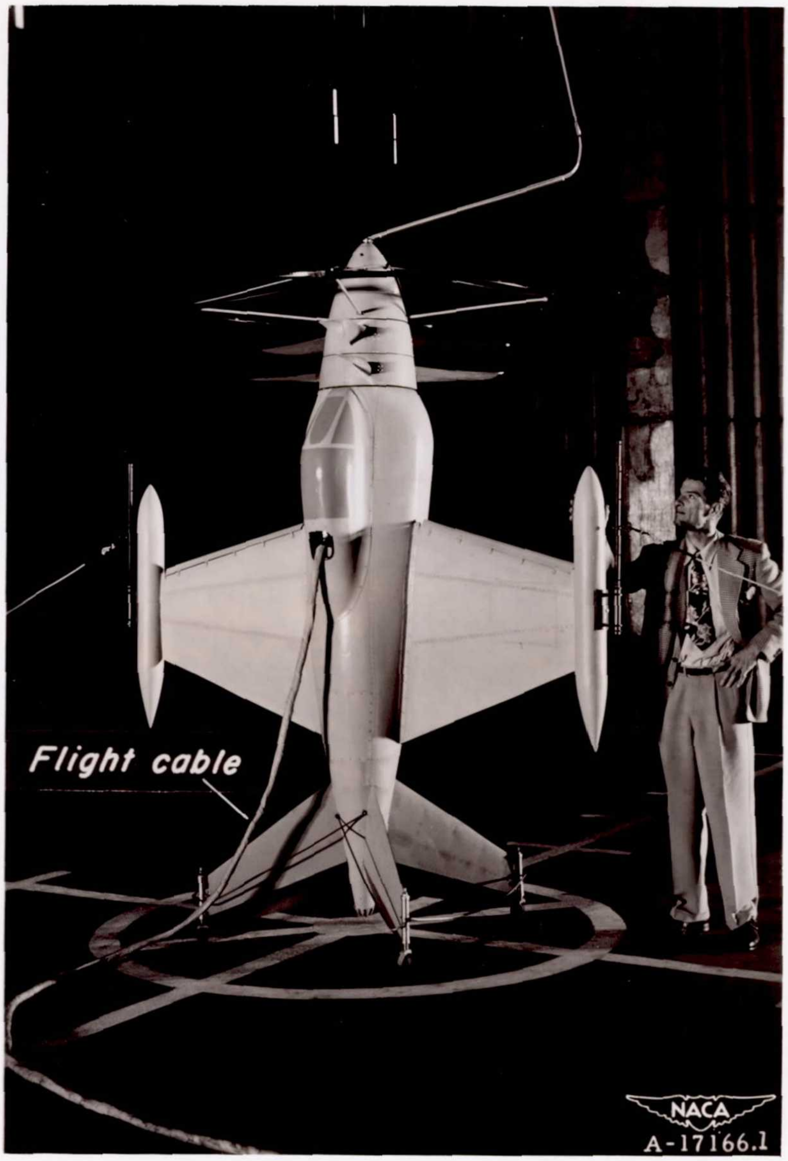

Figure 4.- Photograph of the model with tethering lines and flight cable attached for hovering flight.

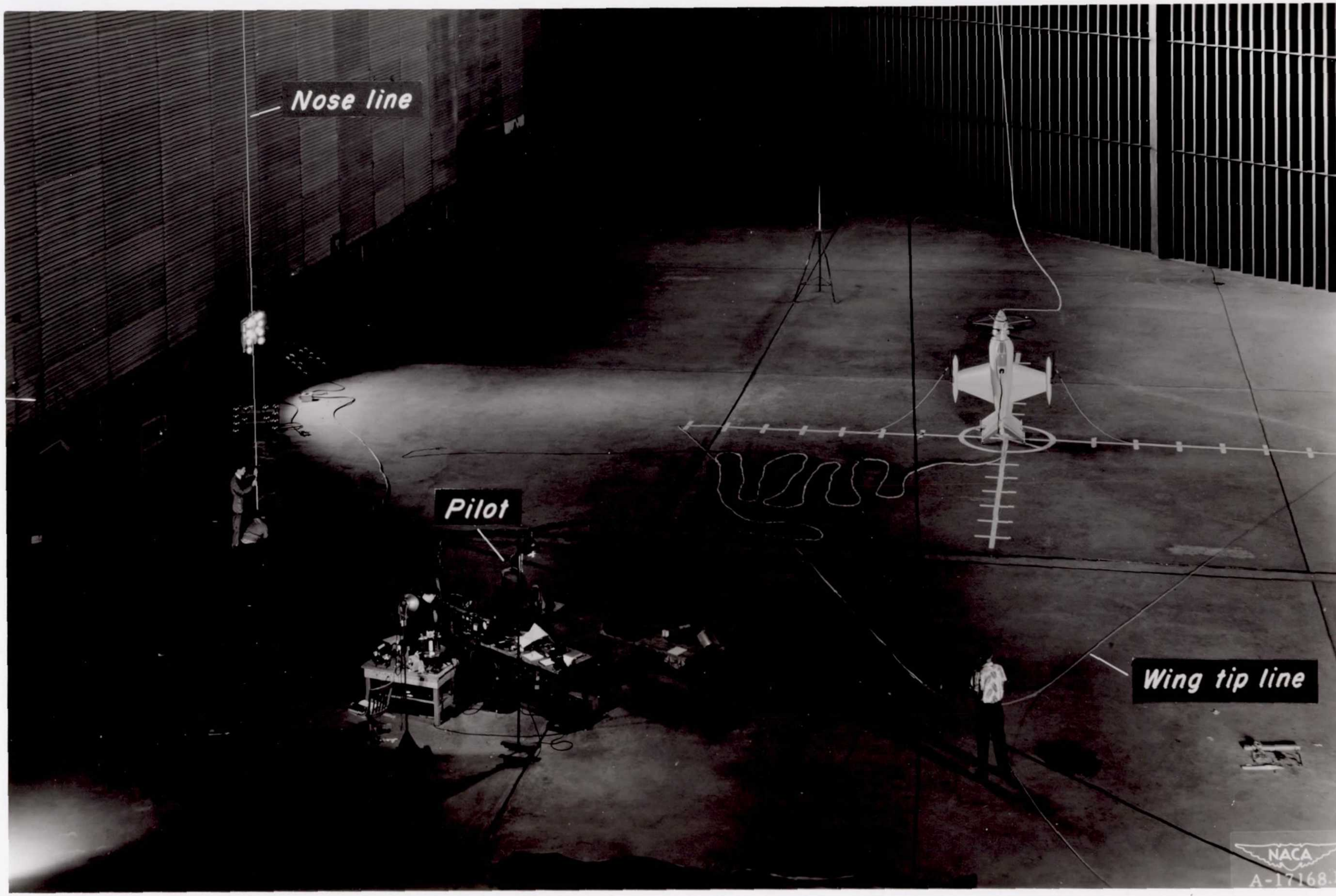

Figure 5.-- View of the model and test equipment as arranged for the low-speed pitch-translation flights in the return passage of the wind tunnel.

Figure 6.- Sketch of test setup for the high-speed translation flights in the wind-tunnel test section.

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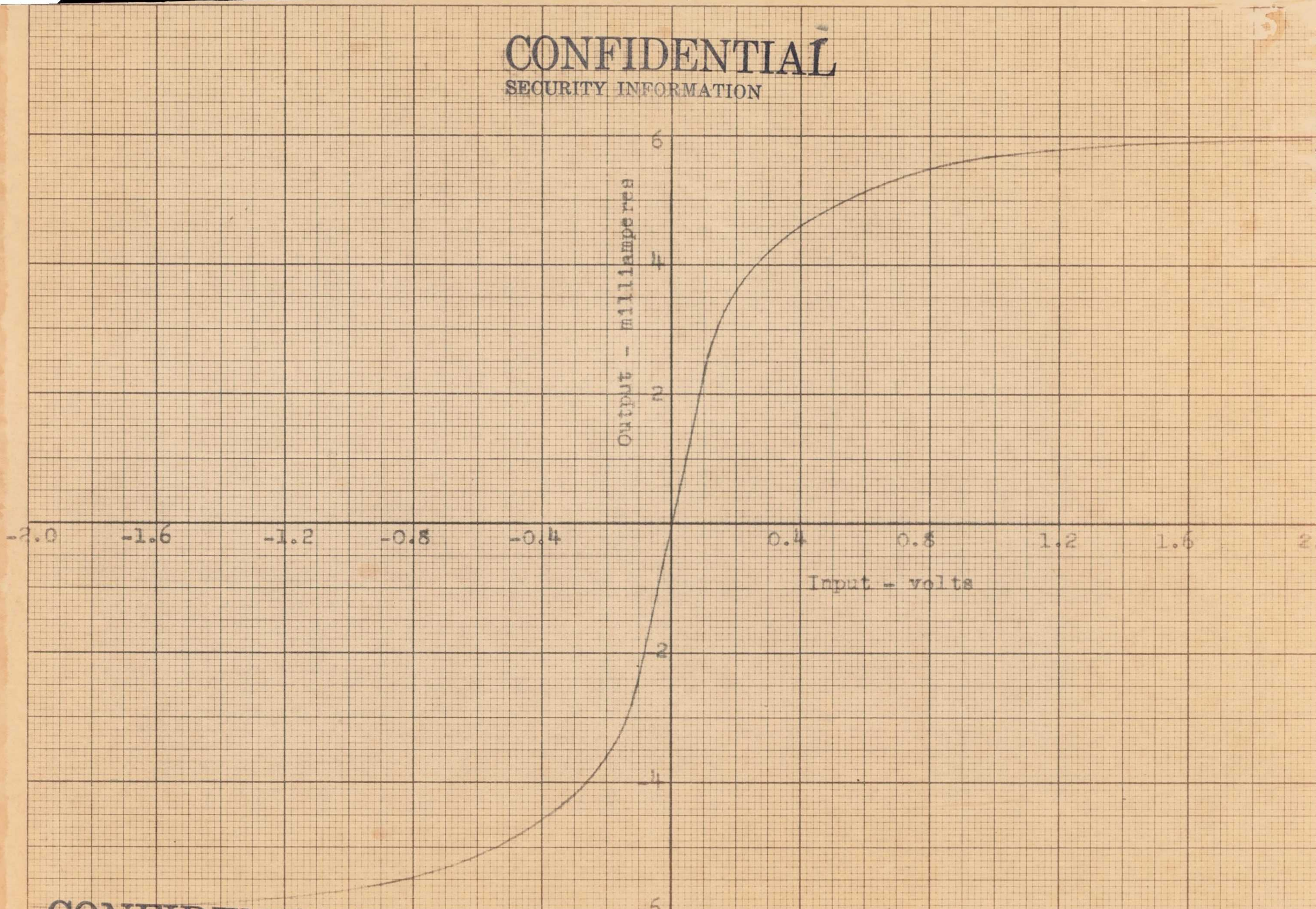

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Figure 7.- Amplifier gain characteristics.

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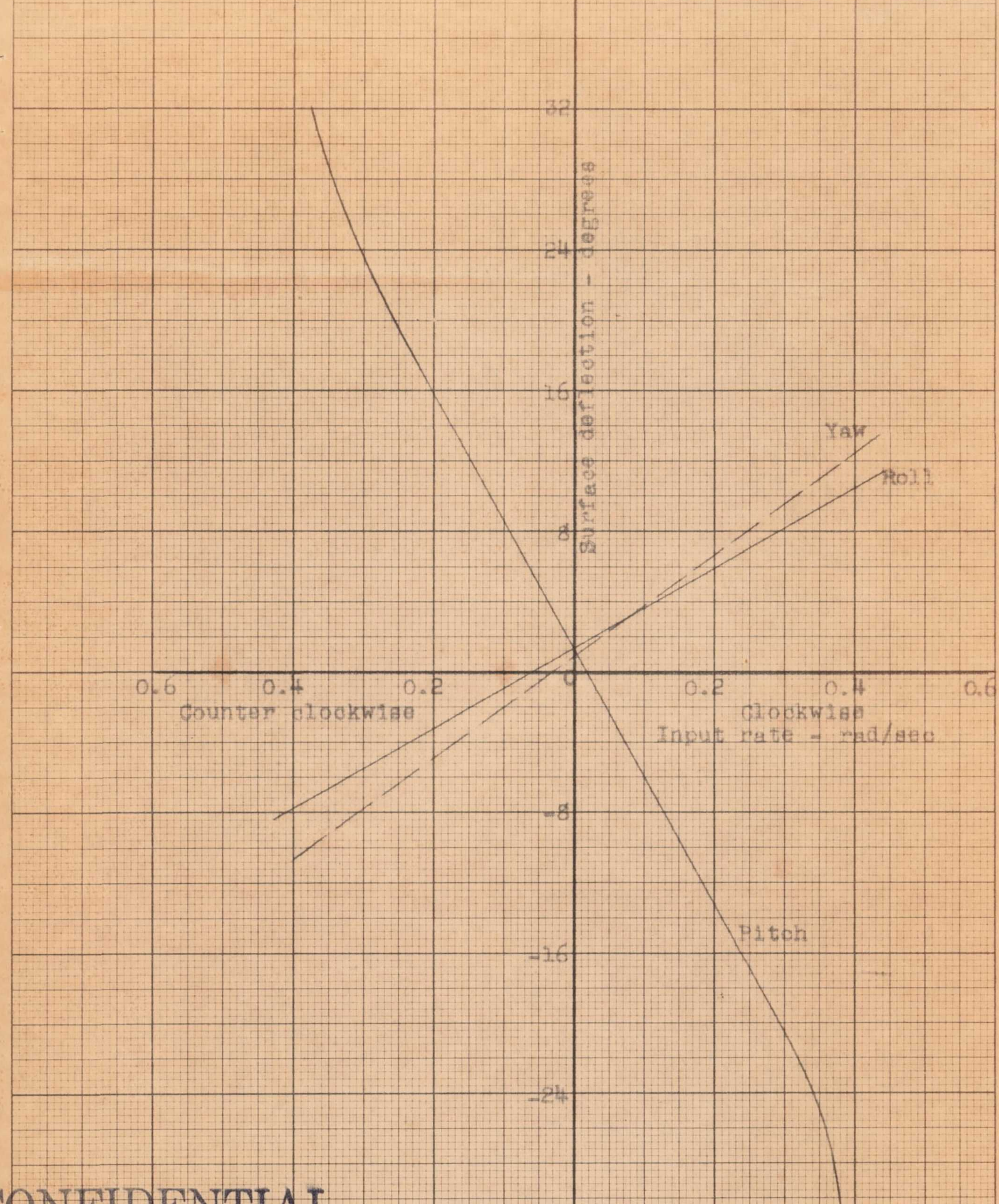

Figure 8.- Rate gyro - servo gearing calibrations for servo no. 2, with a rate setting of 4.0 and a feedback setting of 5.0.

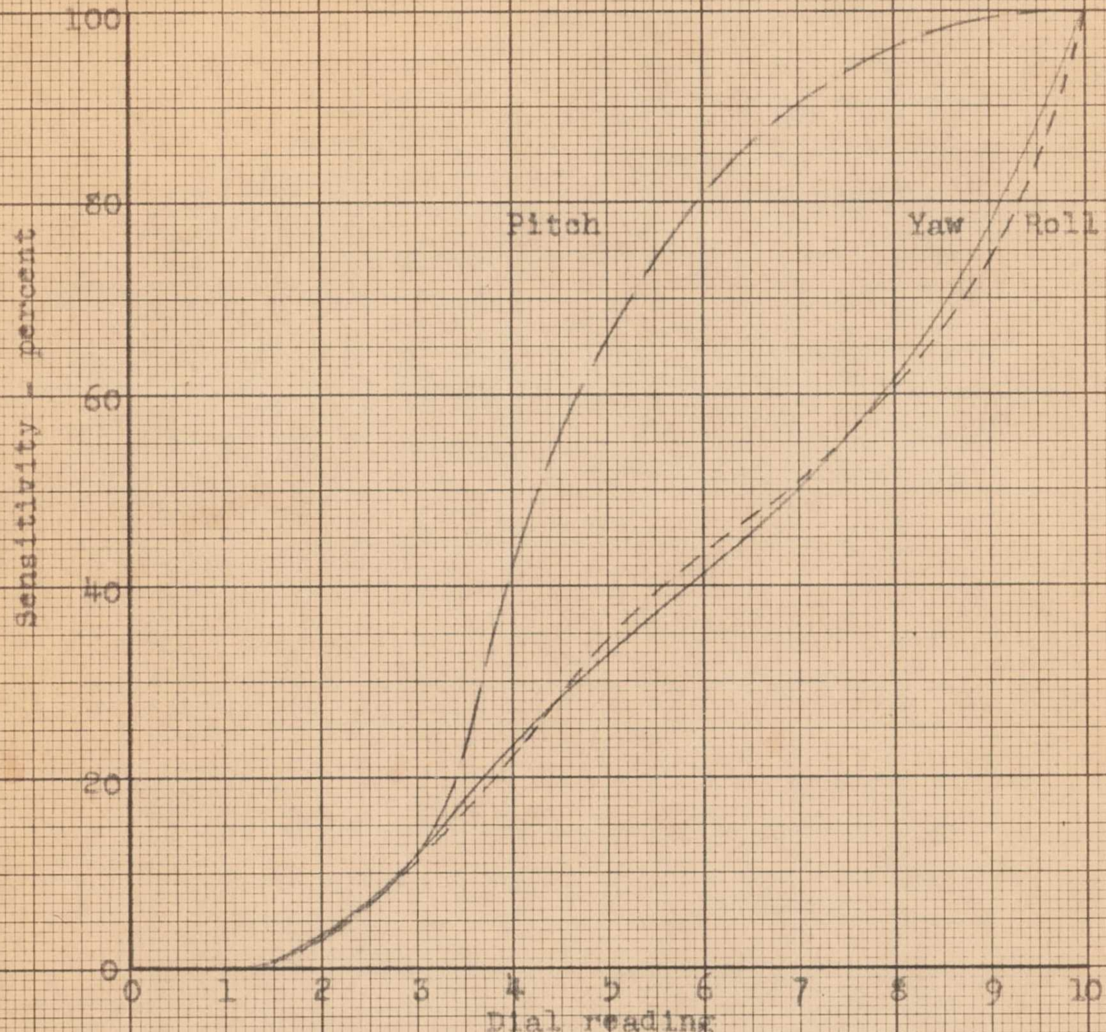

Figure 9.- Rate potentiometer calibrations.

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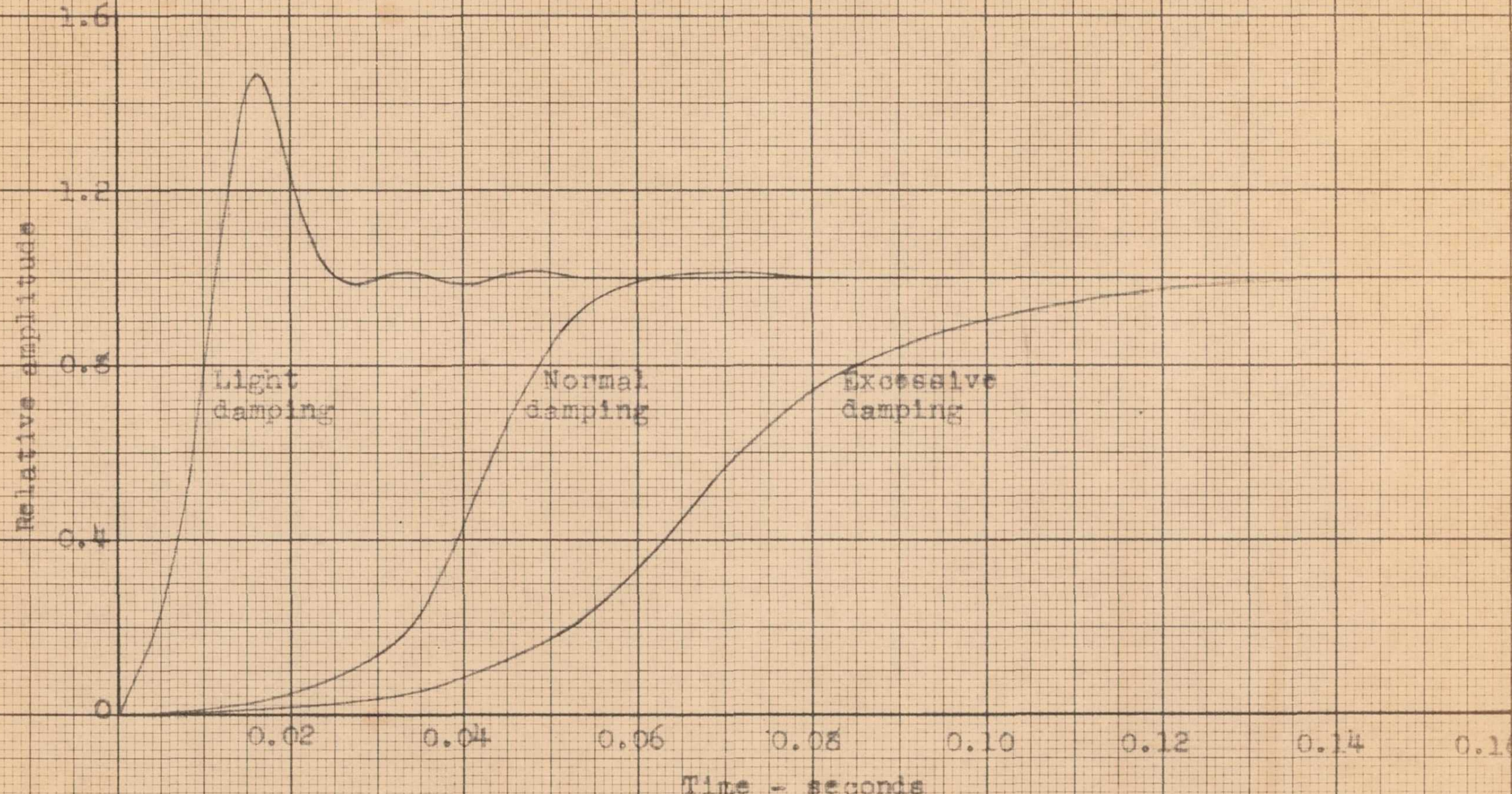

Figure 10.- Transient response of pitch rate gyro.

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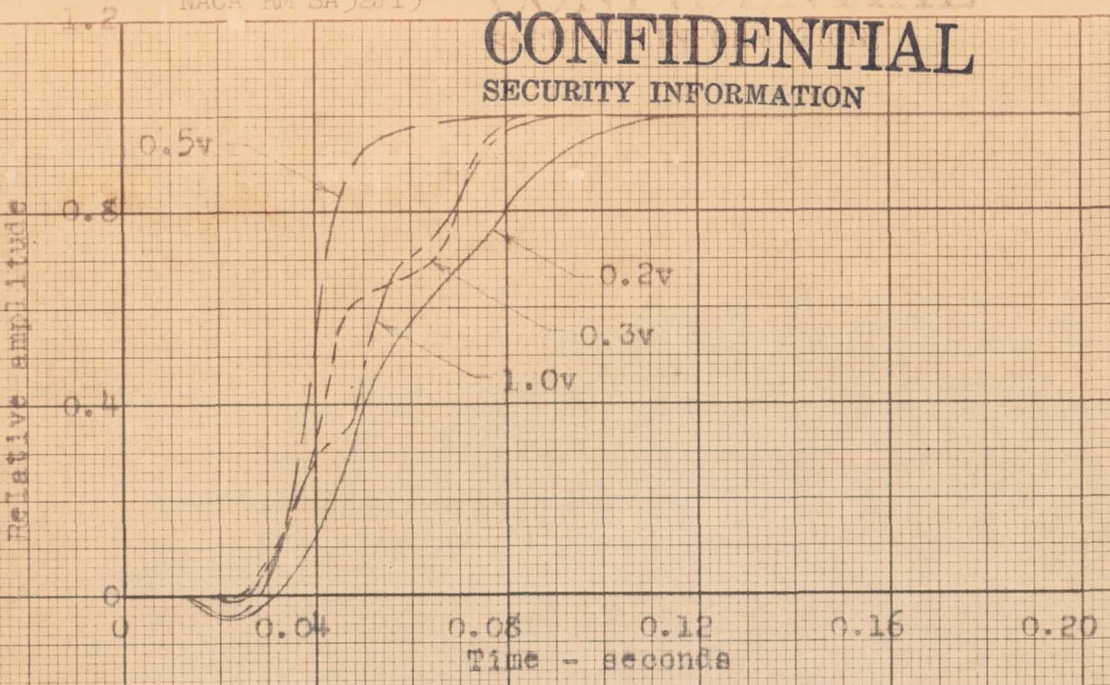
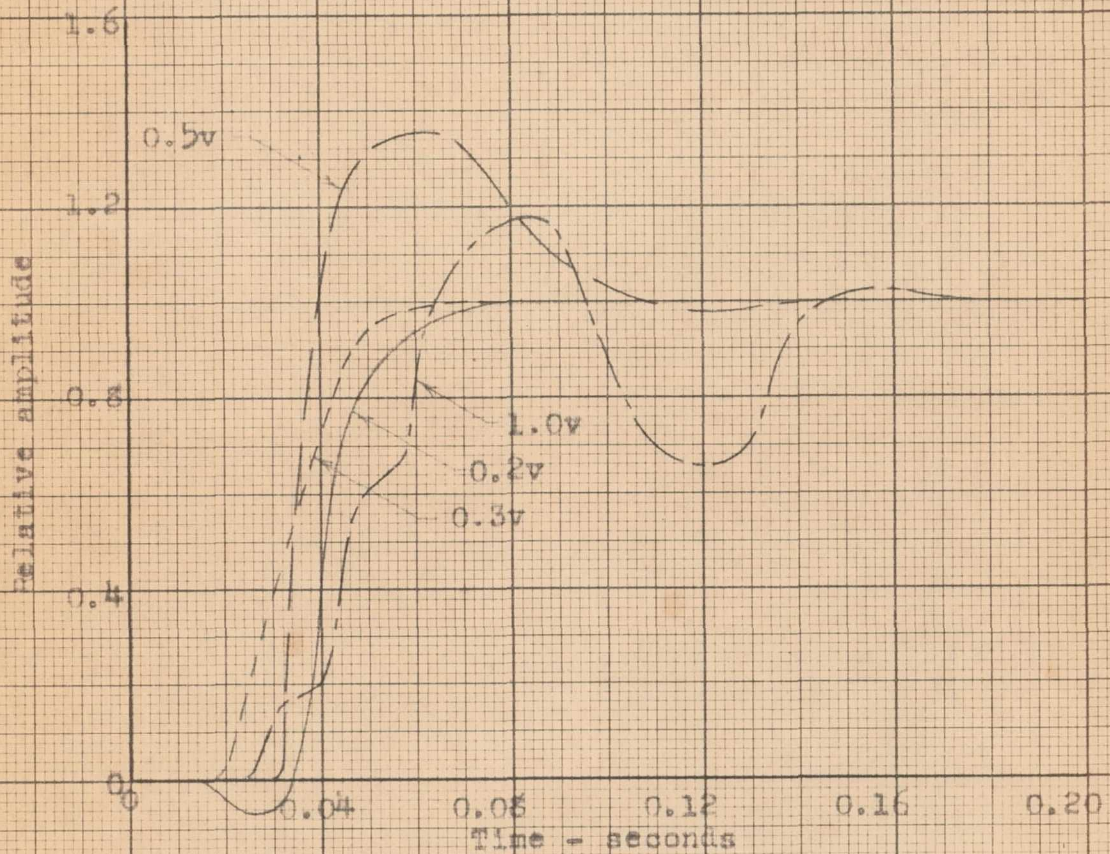
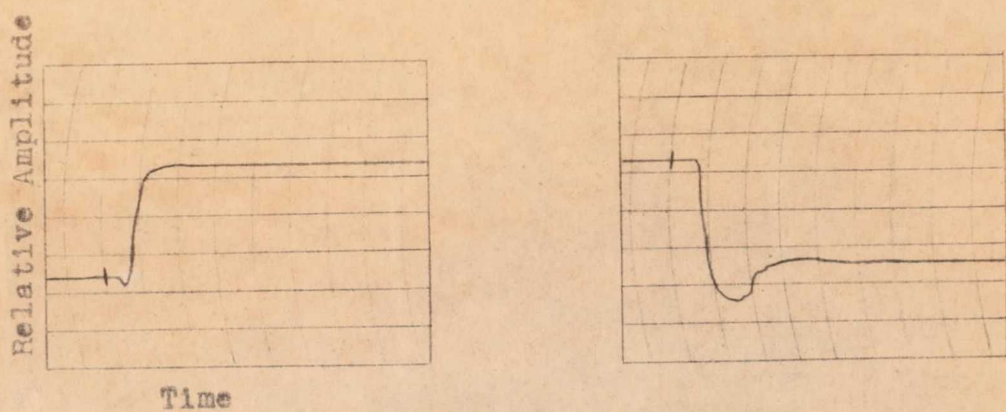


a. Positive direction of motion.

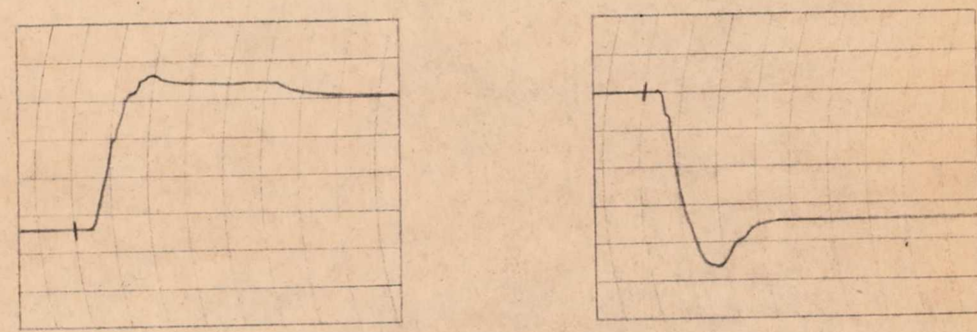


b. Negative direction of motion.

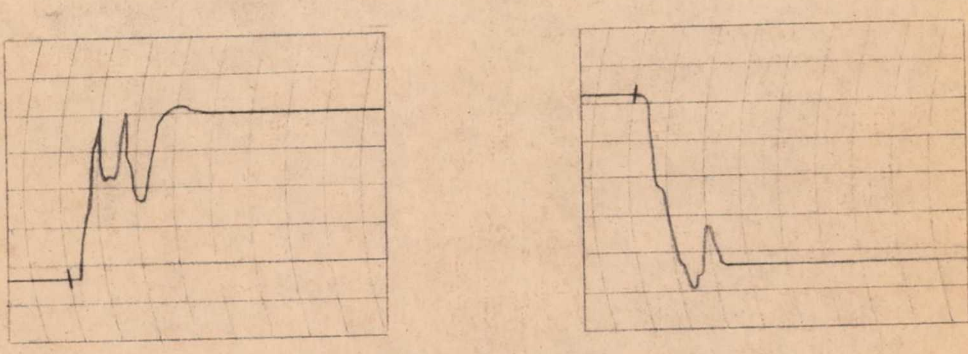
Figure 11.- Transient response of servo no. 1 for various step input voltages.



a. Servo no. 1

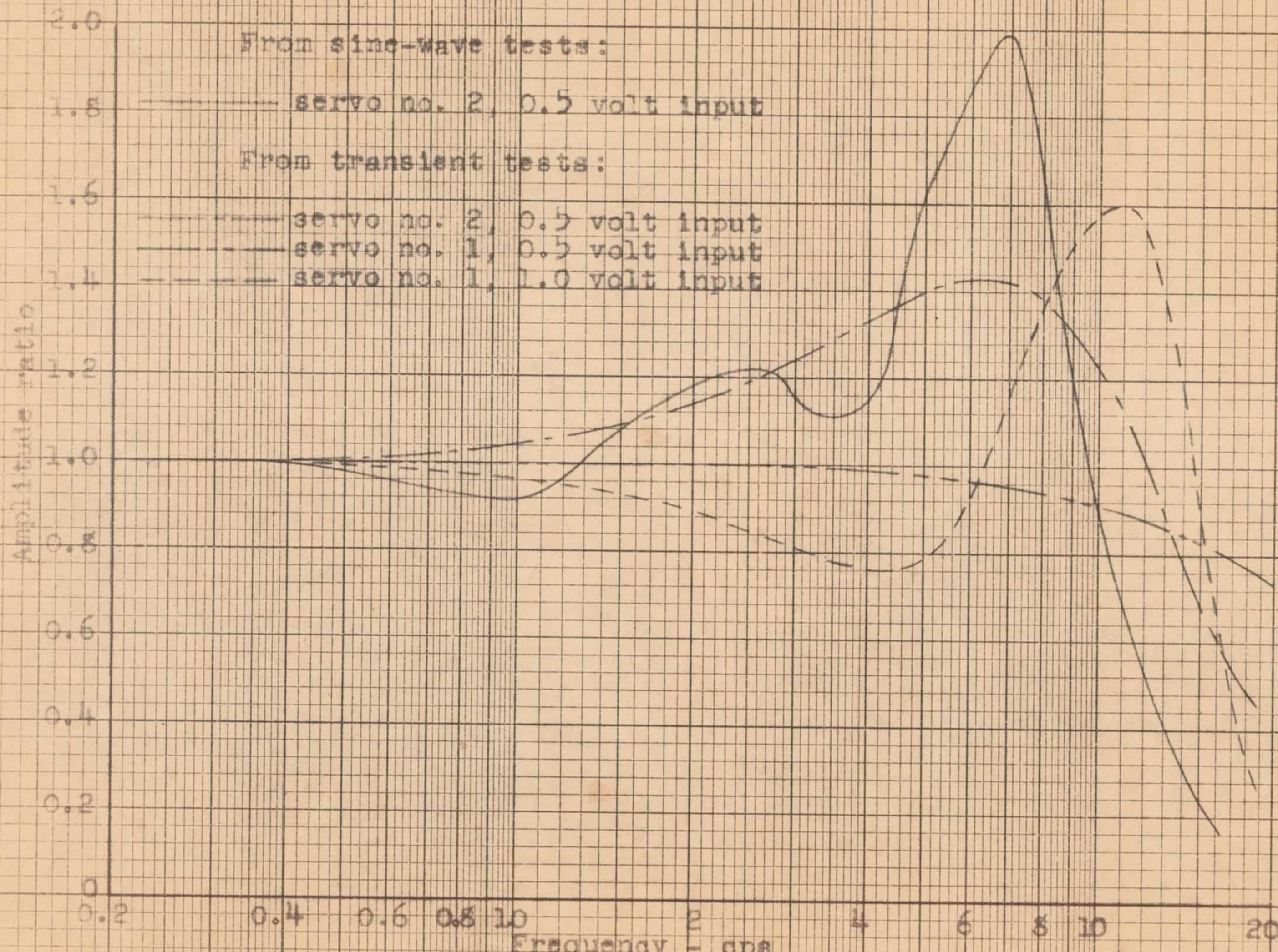


b. Servo no. 2



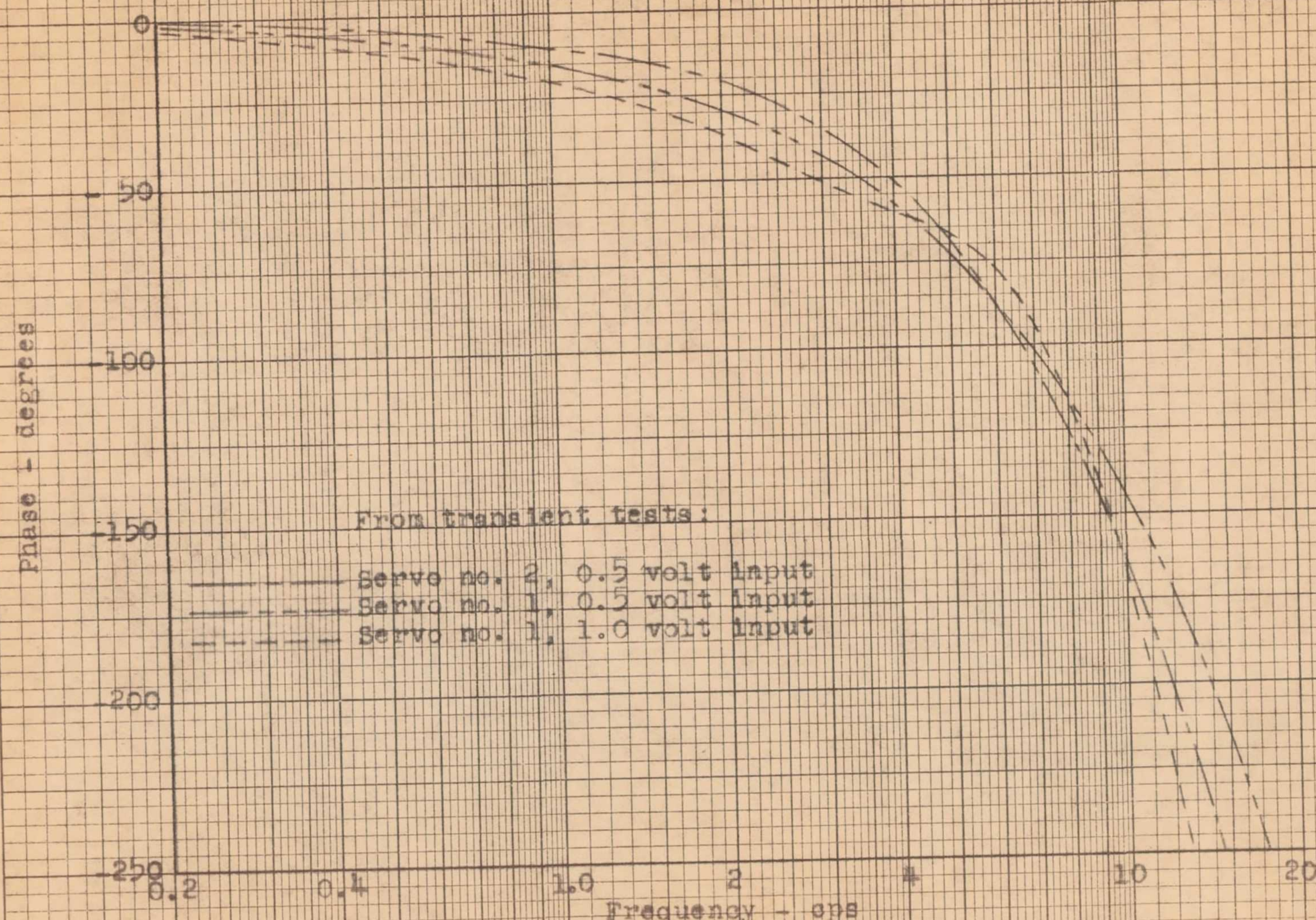
c. Servo no. 4

Figure 12.- Transient responses of three servos for 0.5-volt step-input signal.



a. Amplitude ratio.

Figure 13.- Frequency response of servo system.



b. Phase.

Figure 13.- Concluded.

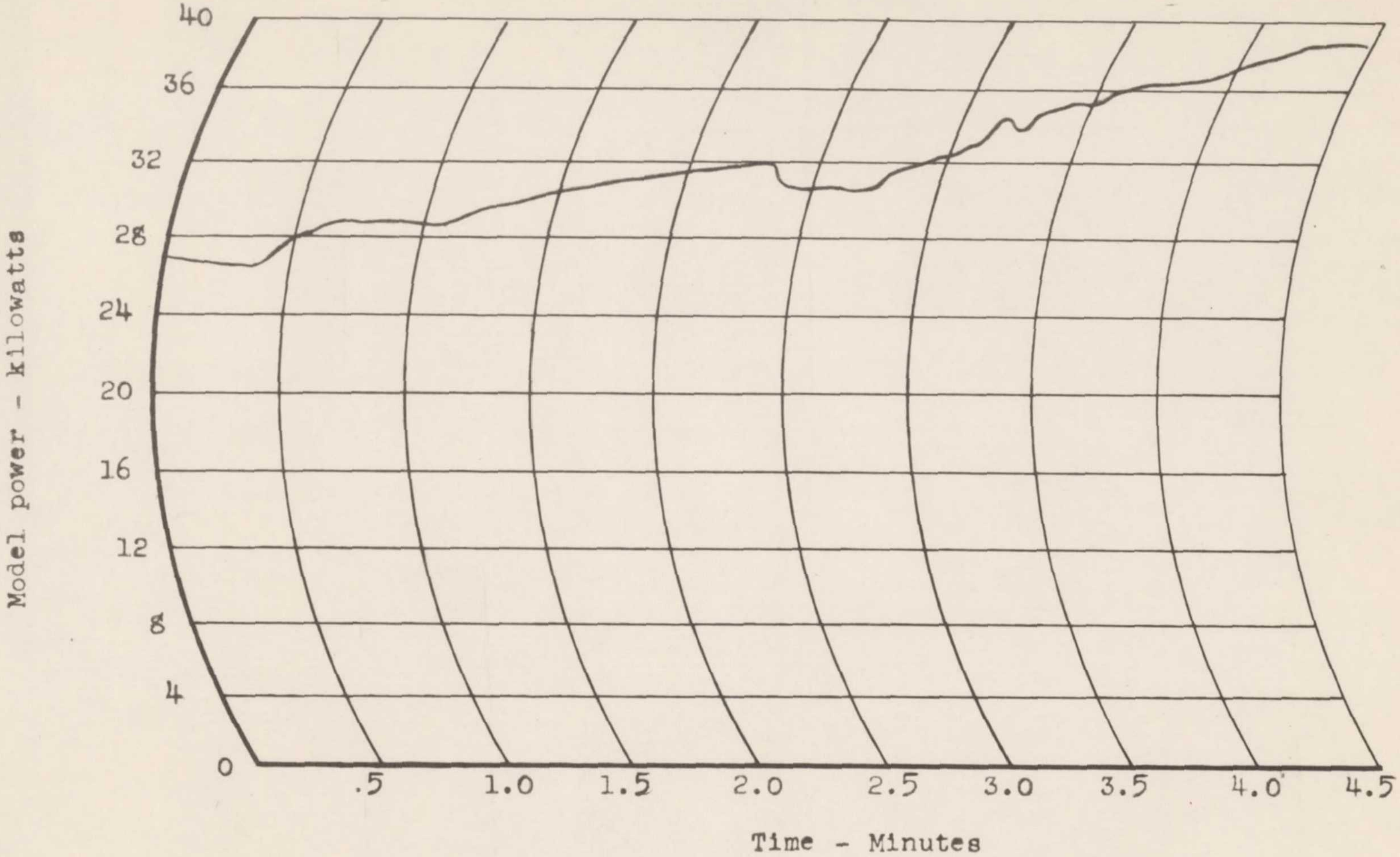


Figure 14.- Time history of variation in power input to model motors during a slow-down transition from 60 fps to less than 10 fps.