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SUMMARY

The VTOL flight test stand at Ames Research Center, built for testing control concepts on the X-14B VSS aircraft in hover, is described. This stand permits realistic and safe piloted evaluation and checkout of various control systems and of parameter variations within each system to determine acceptability to the pilot. Pilots can use it as a practical training tool to practice procedures and flying techniques and become familiar with the aircraft characteristics. Some examples of test experience are given.

The test stand allows the X14B to maneuver in hover from centered position ±9.7° in roll and ±9.3° in pitch, about ±6° in yaw, and ±15 cm in vertical translation. The unique vertical "free flight" freedom enables study of lift-offs and landings with power conditions duplicated. The response on the stand agrees well with that measured in free hovering flight, and pilot comments confirm this. The stand was used initially for checking hardware modifications to the X-14B aircraft control system. It has also been used with the X-14B to study the effects on handling qualities of a wide variation in control characteristics of an attitude command system.

INTRODUCTION

Flight research to investigate advanced VTOL aircraft control concepts in hovering flight can be accomplished more efficiently and with greater safety if appropriate equipment is available for preflight testing and pilot familiarization. The equipment should provide for piloted operation and for test of all critical aircraft systems with minimal jeopardy to the pilot, aircraft, and other personnel. It must also permit the pilot to become familiar with the aircraft's response to the control systems in both normal and emergency situations in an environment that simulates hovering flight as closely as practicable.

The requirements can be met by a test stand that allows the aircraft to lift off under its own power in a manner that simulates hovering flight. The support must permit attitude motion in response to control inputs, and all systems should be operable during the test to subject all components to realistic temperatures and vibrations. In addition, provision should be made to monitor the performance of critical aircraft systems. A test stand meeting the above requirements has been built and used with the X-14B VTOL variable stability aircraft.

The X-14B is a jet lift VTOL which utilizes engine bleed air for angular control in roll, pitch, and yaw. It is equipped with a variable stability system (VSS) shown in figure 1, which can function in either a response feedback mode or a digital computerized model following mode. Since the test stand allows for limited motion in the vertical axis as well as the 3 angular axes, it provides safe means for exploring variations and limits in control sensitivity, system damping and stiffness in much the same manner as the ground-based simulator study in reference 1. This was, in fact, done to provide a preliminary verification of the attitude command system study of reference 1, and to provide an envelope of safe operation for a final free flight verification of the simulator results.

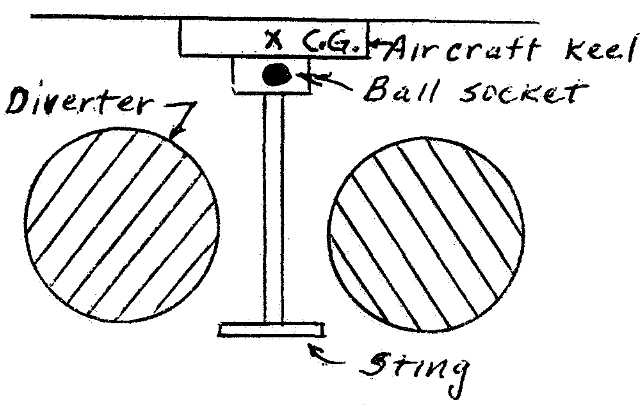
This report describes the important features of the test stand, discusses modes of operation and some of the test experience using the X-14B aircraft, including a comparison of test stand results with simulator results for an attitude command system.

DESCRIPTION OF STAND

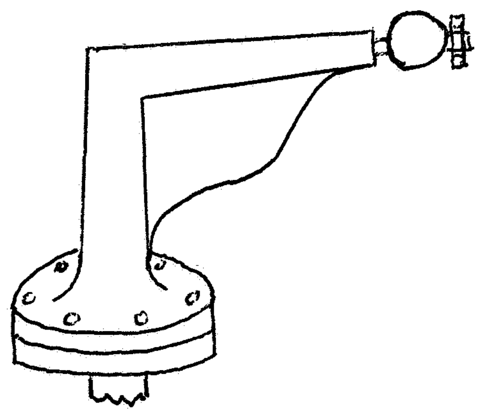
The aircraft is mounted on the test stand as shown in the overall view of figure 2. A ball-socket is fastened to the aircraft and provides a point of rotation near the center of gravity of the aircraft. The ball is supported by a sting which is fastened to the tether mechanism. This mechanism allows limited vertical translation, and is, in turn, fastened to a T-shaped section of the ground support grating that can be elevated. Motion restraints are provided between the T-section and the aircraft. There is an additional area of fixed grating around the T-section which covers a pit that is lined with concrete. A hydraulic lift provides a means to raise the T-section to a selected height above the surrounding grating, as shown in the photo of figure 2. Further description of these parts is given in the following sections.

Sting

The aircraft is supported to allow roll, pitch, and yaw motion about a point close to the center of gravity (CG). For the X-14B a very compact ball-socket is used, with the socket attached to the aircraft keel. This support point is at the lateral and longitudinal design CG but is roughly 5 cm below the vertical CG to clear structure. There is very limited clearance below this point between the exhaust diverters of the two jet engines. These diverters direct the thrust vertically for hovering flight. The ball is 5.08 cm in diameter; it is mounted on a slender sting to permit as much motion as possible. The sting is positioned between the engines and forward of the center of gravity. The adjacent sketch of the sting, and also the end view of the sting and aircraft, show the parts described and



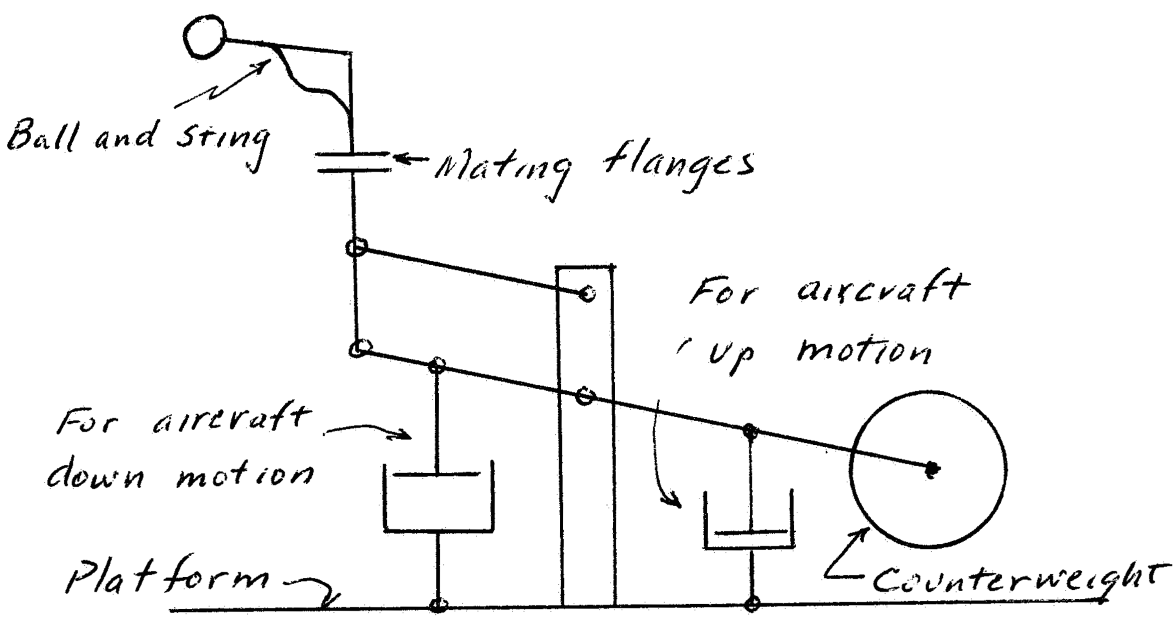
End view of Sting and Aircraft


Sting

their relative positions. The sting is made as shown to keep it stiff but give maximum clearance. This design was chosen to allow the maximum roll and pitch motion at the expense of yaw motion which is the least important.

Tether

The tether (fig. 3) is mounted on the T-section of grating. It consists of a double pantograph arrangement to permit vertical motion and restrain sideward or forward motion. Two single-acting dampers are mounted as shown in the sketch below, one for up motion and the other for down motion. These dampers limit the rate at which the aircraft can hit its vertical limits. In addition, the damper controlling up motion has spacers on its shaft to limit the amount of vertical motion of the aircraft. The total vertical motion



Simplified tether mechanism

available is about 46 cm. Since the net upward force, assuming a thrust-to-weight ratio of 1.1, is about 185 kg for the X-14B, this damper is fairly light. The heavier damper, for the downward direction of motion, limits the velocity to about 60 percent of free fall velocity. The counterweight completely balances the weight of the tether mechanism.

Restraints

It was necessary to limit rotational motion to avoid hitting the engine diverters against the sting support. The main gear acts as stops for the aircraft in roll, as illustrated in the sketch below, and the nose gear for pitch down. For pitch up and yawing motions special restraints were devised using aircraft cables

a) no roll b) roll limit

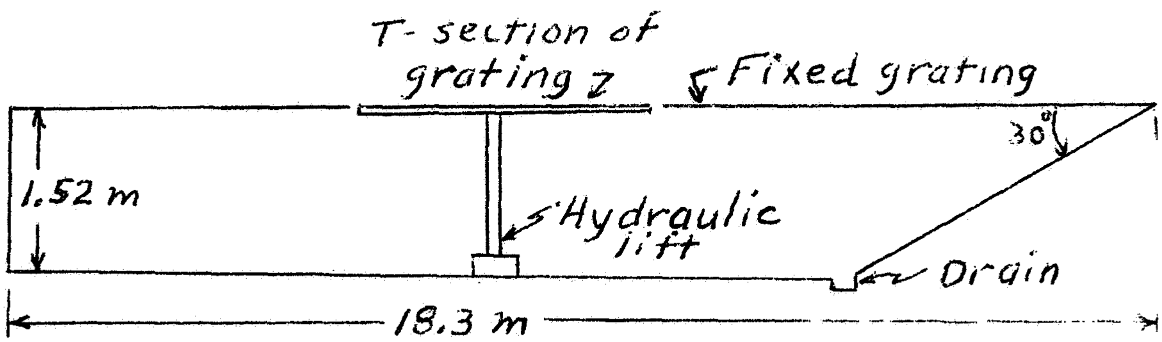
Gear as roll restraint

and short lengths of prestretched nylon parachute cord to act as energy absorbers; these are attached to anchor points on the grating. As can be visualized from the sketch, the greater the amount of vertical motion permitted by the tether, the greater the angular freedom in roll and pitch down before the gear hits the platform. Only 30 cm of vertical lift gives ample rotational capability. A lockout device is provided on each gear to prevent compression and consequent excess travel. Similarly the gear is restrained to keep it from extending when the aircraft lifts off. The tires allow some energy absorption on impact; however, to avoid damaging the aircraft in case of extreme shock load, a rupture link is put in these lockout devices.

The ranges of motion for a 30 cm vertical liftoff are: ±9.7° in roll, ±9.3° in pitch, and about ±6° in yaw. An additional several degrees are available for snubbing or stopping the action before any structural interference is reached. While additional motion could be obtained if vertical tether motion were increased, it was not found necessary to provide larger motions for pilot realism. In fact, the roll and pitch limits above were selected to preclude uncomfortably large attitudes for the pilot. A picture taken when establishing maximum allowable motions is shown in figure 4. The motions here are approximately 13° in roll and 18° in pitch. These extremes of motion exceed those that would be used for piloted testing on the stand.

Pit, grating, and hydraulic lift

The concrete pit is 15.2 by 18.3 m, about 1.52 m deep, and is covered by a grating. A side view is shown below and an aerial photo of the area is shown in figure 5. The grating is heavy bridge decking welded to support beams and capable of supporting loads of 4535 kg per wheel, but still permitting air to pass through freely.



Cross section of pit

The 30° sloping end is at the downwind side of prevailing winds to aid in carrying away engine exhausts. The floor of the pit also slopes slightly to that end and water drainage is provided. The capacity of the hydraulic lift is 6800 kg and it can be raised to 3.05 m. The hydraulic lift pump is in an equipment pit some 25 m away; it has a remote control cable so that the operator can be close to the motion he controls. The liftable portion is in the form of a T-section (see the dark portion of fig. 5) which, when elevated, can be rotated easily by hand to permit the aircraft to be aligned with respect to the wind as desired. Normally, cable stops are attached so it will not rotate with the wind, and these same cables are used to limit the platform height when it is raised. A 1.52 m level has not been exceeded so far because of considerations of safety of pilot egress. The rise time to 3.05 m is 130 sec and the time to lower is 95 sec.

Auxiliary equipment, operating information, and characteristics of the test stand are described in appendix A.

RESULTS

Since the completion of the test stand it has been used in two phases of testing relating to the X-14B programs. The first application was in the checkout of the hardware following an extensive modification to the airplane variable stability system controls. The modifications included a new bleed air valving, ducting, and actuator system, an analog autopilot, and a digital computer for prefilter model following control studies (see fig. 1). More details on the system modifications may be found in references 2 and 3.

The second application was in a brief study conducted to provide partial verification of some generalized simulation studies and to establish safe operating limits for subsequent tests in free flight.

These applications are described in more detail in the following sections in order to illustrate the utility of the test stand.

In the first application the test stand was used first to conduct a hardware check of the control system. This was achieved largely through frequency response tests conducted with the airplane hovering on the stand. The tests were accomplished by exciting the aircraft control system at frequencies of from .1 to 1 Hz through the external cabling from the test trailer. During these tests the pilot performed the lift-off, leveled the aircraft, and maintained the necessary power for hover. A representative record of these data is shown in figure 6. This type of hands-off measurement would be most difficult to make safely in flight.

During additional hardware check runs a faulty roll accelerometer was detected as noisy, causing control difficulty for the pilot. Such a detection again points out the virtue of such a test stand facility.

To assess the validity of the test stand a comparison of system step responses on the test stand and in free flight was made. Figure 7 exhibits step response data for the X-14B in the model mode for the pitch axis, both on the test stand and in hover at altitude. These data show the good correlation of angular response.

In the second application the test stand was used for verification of the VSS software and for determining the safe bounds for variations in the control characteristics.

The variation and optimization of types of control systems have been the subject of several ground simulations (e.g., refs. 1 and 4). These studies have considered the desirable bands of control characteristics (i.e., sensitivity, damping, and stiffness) for angular rate, attitude, and translational rate command systems in near hover flight. Since the extremes of these bands may represent unacceptable control characteristics it was desirable to define a safe envelope prior to undertaking free flight investigations of these simulator results. In addition, the results from the test stand, in themselves, provide a preliminary verification of the simulator results.

Tests utilizing the X-14B on the test stand focussed on an attitude command system. Figure 8 contains key results from a simulator study of an attitude command system (ref. 1). That study involved a parametric variation of an attitude command system for pitch and roll, where the Cooper-Harper pilot rating (PR) was the primary performance criterion. Shown in figure 8a are optimum combinations of damping ratio (ξ) and natural frequency (ω_η) of an attitude command system in pitch and roll. Figure 8b exhibits the influence of control power and natural frequency on pilot rating in roll. Superimposed on figure 8b is a line representing the maximum available control power of the X-14B in roll (1.3 r/s^2). The corresponding maximum in pitch is .8 r/s^2.

Similar attitude control characteristics were implemented on the X-14B while operating on the test stand. Pilot rating was used in the evaluation for which small control reversals was the task. The systems responses were monitored in the test site trailer to provide indication of possible aircraft restraint limiting or nozzle saturation which could lead to pilot-induced-oscillations (PIO). The tests were conducted using both the response feedback mode of control and the model following mode.

Figure 9 shows the results in roll of test stand runs for an attitude command system using the response feedback mode. Shown for comparison is the optimum contour for a pilot rating of 2-1/2 resulting from the simulator (ref. 1). The system bounds represent physical limits of the system potentiometers on the X-14B.

Figure 10 is for a similar case, but using the model following mode. The pilot noted a definite increase in steadiness of control with the model following system over the response feedback system for similar control characteristics. This was anticipated since the model of the model following system is not subject to "real world" disturbances and variations and thus provides a more precise control. This added steadiness may explain, at lease in part, the increased envelope of PR-3 derived from the model following mode over the response feedback mode of operation.

These test stand results correspond rather well with the moving-base simulator results. The test stand results were of course devoid of linear longitudinal and lateral motion. The pilot generally preferred higher damping on the test stand than in the simulator.

The ultimate test of any aircraft control system is the assessment of improved handling qualities in free flight. Indeed, this is true here, for the test stand results with the X-14B provides only a preliminary evaluation and verification of the simulator results. Accordingly, a free flight hover validation of a subset of the cases considered on the test stand is planned.

CONCLUSIONS

The test stand described in this report has been used for some 80 tethered flights of the X-14B with a wide variation in control characteristics. Certain conclusions regarding its usefulness and of the systems thus far investigated can be made.

1. The test stand provides a repeatable and controlled environment in which to conduct system checks and variations. Malfunctions exposed in stand operations have confirmed its value for initial hardware and software checks of a new or modified system.
2. The stand permits the pilot to familiarize himself with the controls and characteristics of the system and also the aircraft/engine response; this is especially important in VTOL landings.
3. The test stand gives longer test time than going to altitude for hover, and so reduces the number of flights needed for initial system checkout.
4. The stand, while restricted in linear motion, provides a realistic yet safe means for investigating angular control characteristics prior to a free flight hover investigation.
5. The test stand permits such procedures as frequency response tests to be conducted. This would be unrealistic to perform in free flight.
6. Step response data on the stand correlated well with free flight step responses.
7. Pilot rating results of variations in control characteristics of an attitude command system in pitch and roll correlated

well with those obtained on the simulator.

8. Preliminary results on the test stand indicate a model following type control system has preferable control characteristics to a response feedback type system.

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1. Greif, R. K., Fry, E. B., Gerdes, R. M. and Gossett, T. D., Effects of Stabilization on VTOL Aircraft in Hovering Flight, NASA TN-D6900, August 1972.

2. Gallagher, J. T., Saworotnow, I., Seeman, R., and Gossett, T. D., A Model Following Variable Stability System for the NASA ARC X-14B, Journal of Aircraft, Vol. 9, No. 7, pp 461-469, July 1972.

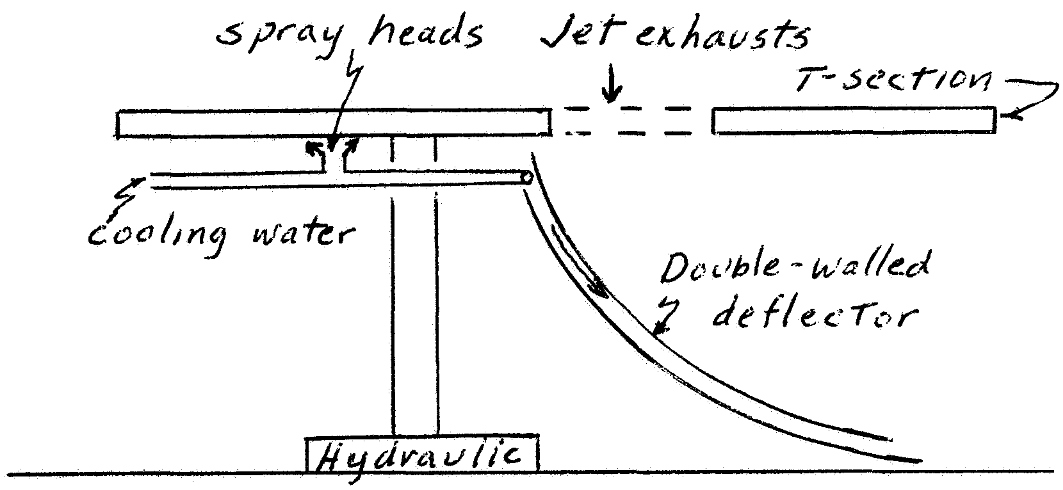
3. Pauli, F. A., Sharpe, T. G., and Rogers, G. R., A Reaction Attitude Control System for Jet VTOL Research Aircraft, NASA TN D-5715, March 1970.

4. Corliss, L. D., and Dugan, D. C., A VTOL Translational Rate Control System Study on a Six-Degree-of-Freedom Motion Simulator, NASA TM X-62,194, October 1972.

APPENDIX A

Auxiliary equipment

A cutout was made in the grating to allow aircraft engine exhaust, when in the vertical direction, to go directly into the pit slightly aft of the hydraulic lift cylinder. The blast from the two jet exhausts spreads out like a mushroom when it hits the floor of the pit and would cause a large temperature rise in the hydraulic cylinder (and eventually in the oil inside). The prevent this, a deflector was installed incorporating a double-walled



Deflector and cooling

construction, so water could be used behind the top deflection plate (see sketch above). Two water spray nozzles are directed to the underside of the T-section for control of heat conducted to the tether mechanism. Thermocouples are mounted in three places and monitored in the trailer to make sure the water is on and temperatures remain within limits. A sump pump is located in the equipment pit to pump the collected water into the drain lines.

For testing purposes it is required to have electrical connections from the ground support equipment (GSE) which was housed some 15 m away in a trailer (see fig. 1 or 4). Data recorders and special equipment to generate electrical test signals are available in the trailer. The connecting cables, which are wrapped with protective sheaths, are large and heavy enough, about 115 kg total, to require substantial support towers and a flexible connection from the last support point into the aircraft control system. This minimizes any forces tending to act on the aircraft to rotate it. The support towers make it convenient to connect special pressure measuring tubes and wires to the aircraft when needed.

Radio communication to the aircraft, and also flight operations center, were available in the trailer to monitor pilot comments and maintain test control.

Operation

Care is taken to maintain the area free of small debris such as weeds, bugs, etc. The aircraft is rolled onto the grating with the sting attached to the ball-socket on its keel. Once in position, the mating flanges between sting and tether are bolted together. The various restraints are connected, the tower closest to the aircraft put in place (it is on the T-section and rises with it), the GSE cables connected to the aircraft, and the remote hydraulic control unit connected. Power is applied to the aircraft and system operational checks are made, including any special GSE recording calibrations.

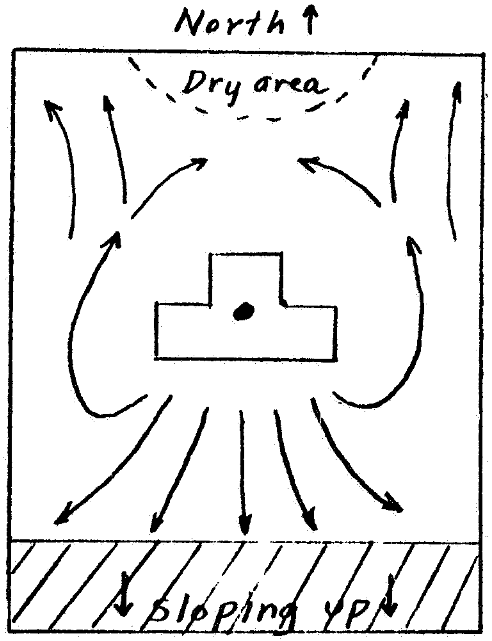
After the pilot completes his preflight check, the cooling water is turned on. The engines are started and then the T-section is raised, if required. The pilot rotates the diverters to direct thrust downward and selects the control system for test. He then lifts the aircraft off the platform by increasing his engine power, just as in flight, and proceeds with his maneuvers or tests. At the end of the tests he throttles back, lands, and goes through his shutdown procedure. The Navy crash crew standing by has the responsibility of rescuing the pilot in event of fire or other emergency.

Operating characteristics

This test stand gives the pilot a feeling very similar to that experienced when flying a VTOL aircraft in hover. One unique feature of the stand that contributes to this feeling of realism is in the way the aircraft flies solely under control of the pilot from its normal on-the-ground position. There is no tilting or rocking or need to support the aircraft in a level position while the pilot enters. In addition, when the engines lift the aircraft off its gear, the ball socket friction is very low, as the ball actually holds the aircraft down in practice, and so has to exert only a normal force of about 185 kg instead of holding up the 1850 kg weight of the aircraft. Also, any added inertia due to support fixtures is practically negligible, which is an important factor with a light aircraft. The small vertical offset from the CG does not present any problem to the pilot. Once the pilot lifts off he can leave the throttle alone since, as fuel is burned, the thrust-to-weight ratio increases, or he can throttle back somewhat (as he would have to do in flight to maintain constant altitude) as the test progresses to save fuel. The pilot is able to hover "off the ball," or in the mid-range of the vertical travel by managing the throttle position very carefully.

Runs have been made with the T-section at ground level and at the 1.52 m level. There is about 2.5 percent increase in lift when at the 1.52 m level compared to ground level, due to decrease in adverse ground effect. Also there is less tendency for reingestion because any wind can carry away the exhaust gases coming up from the pit before they reach the engine intake.

The pattern of airflow seems to vary considerably with local wind velocity and direction, as observed from the blowing of the cooling spray and the water pattern on the floor of the pit. The flow is approximately as sketched below. If the wind is from the north (top of sketch) with velocity greater than 4-5 m/sec, air coming up through the grating blows back into the engine intake area. On several occasions under these conditions, reingestion occurred, the engines lost power, and the aircraft settled back



Airflow pattern

down on the grating. If the wind is from the south, reingestion conditions are worse and also a lot of moisture enters the cockpit. These wind conditions impose limits under which testing can be carried out.

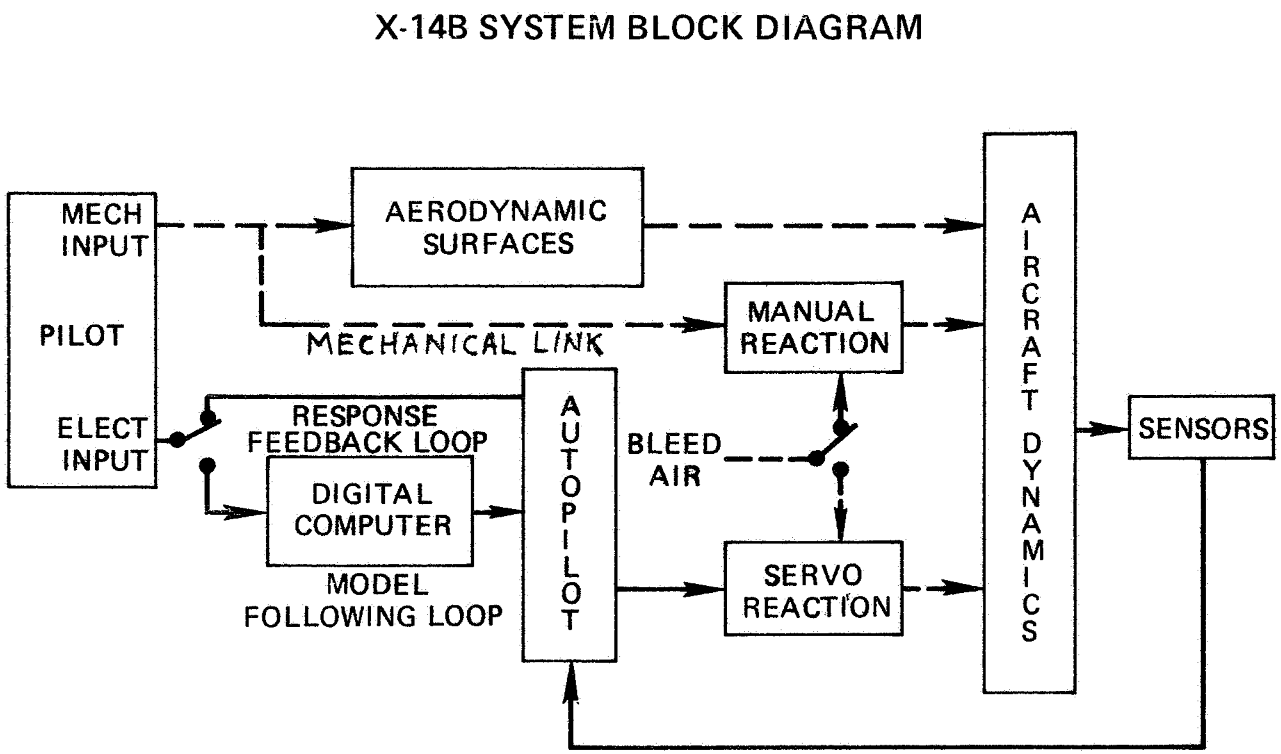


Figure 1. X-14B System block diagram.

Figure 2. Aircraft on test stand.

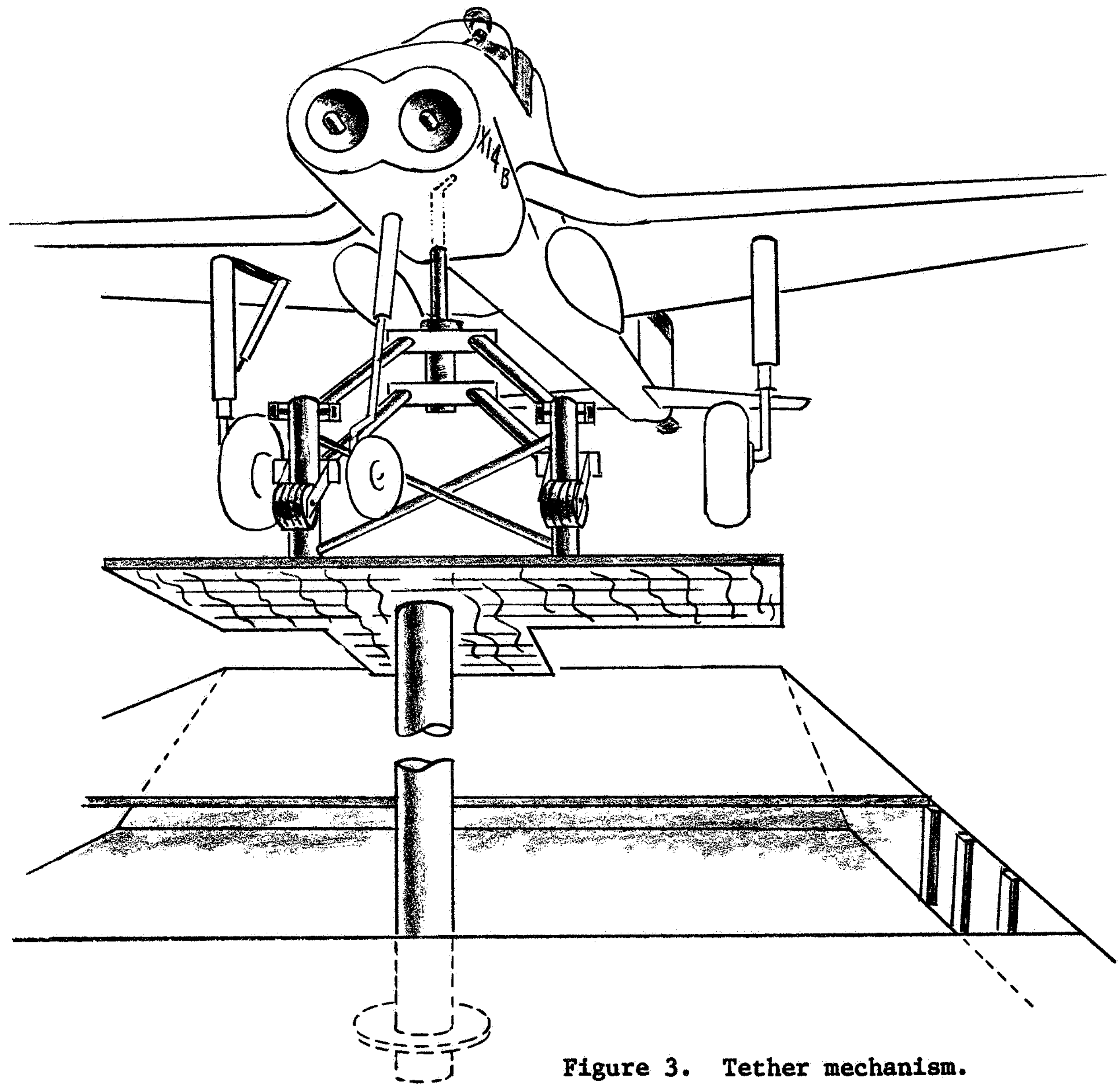


Figure 3. Tether mechanism.

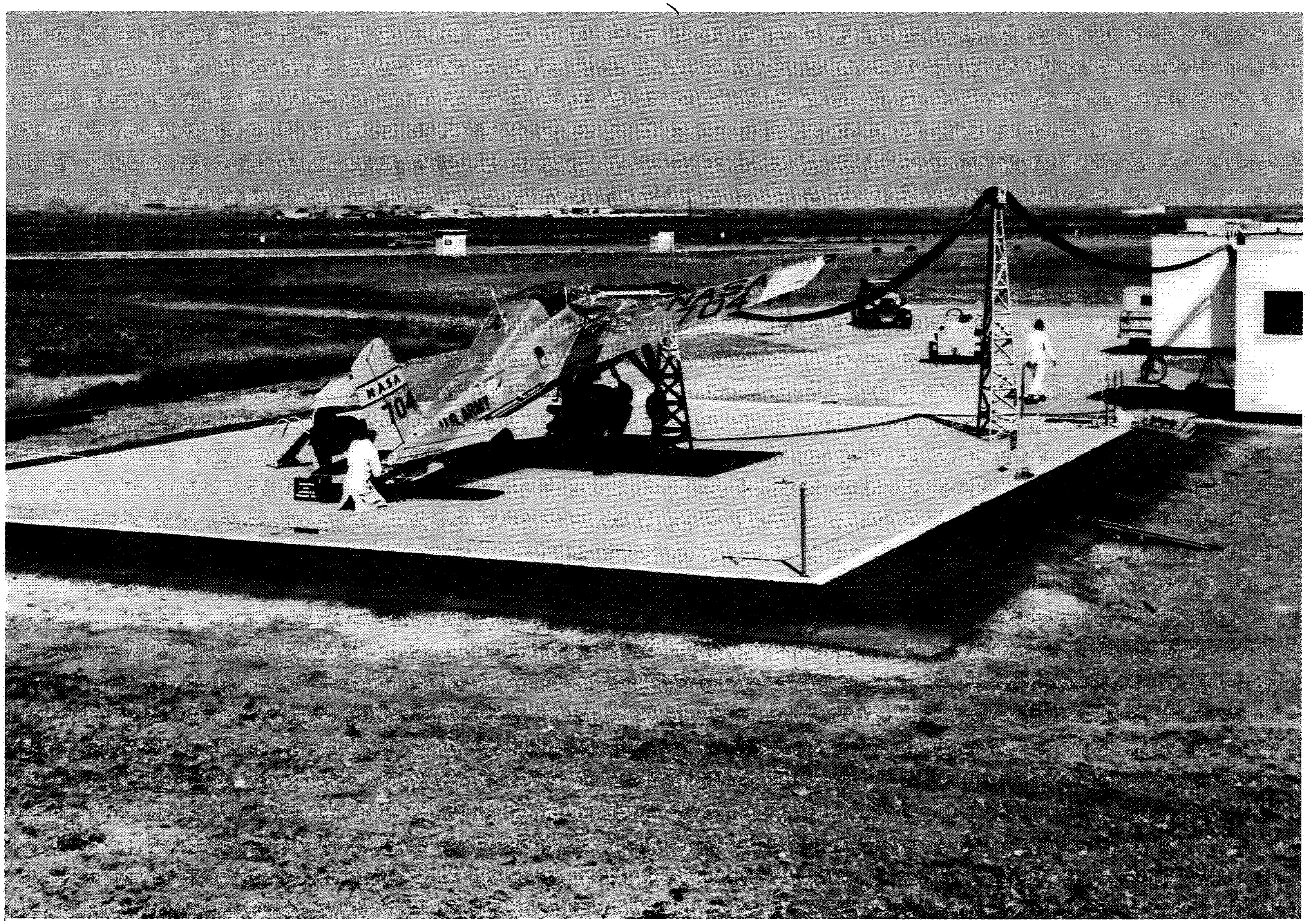


Figure 4. Aircraft at maximum pitch and roll attitudes.

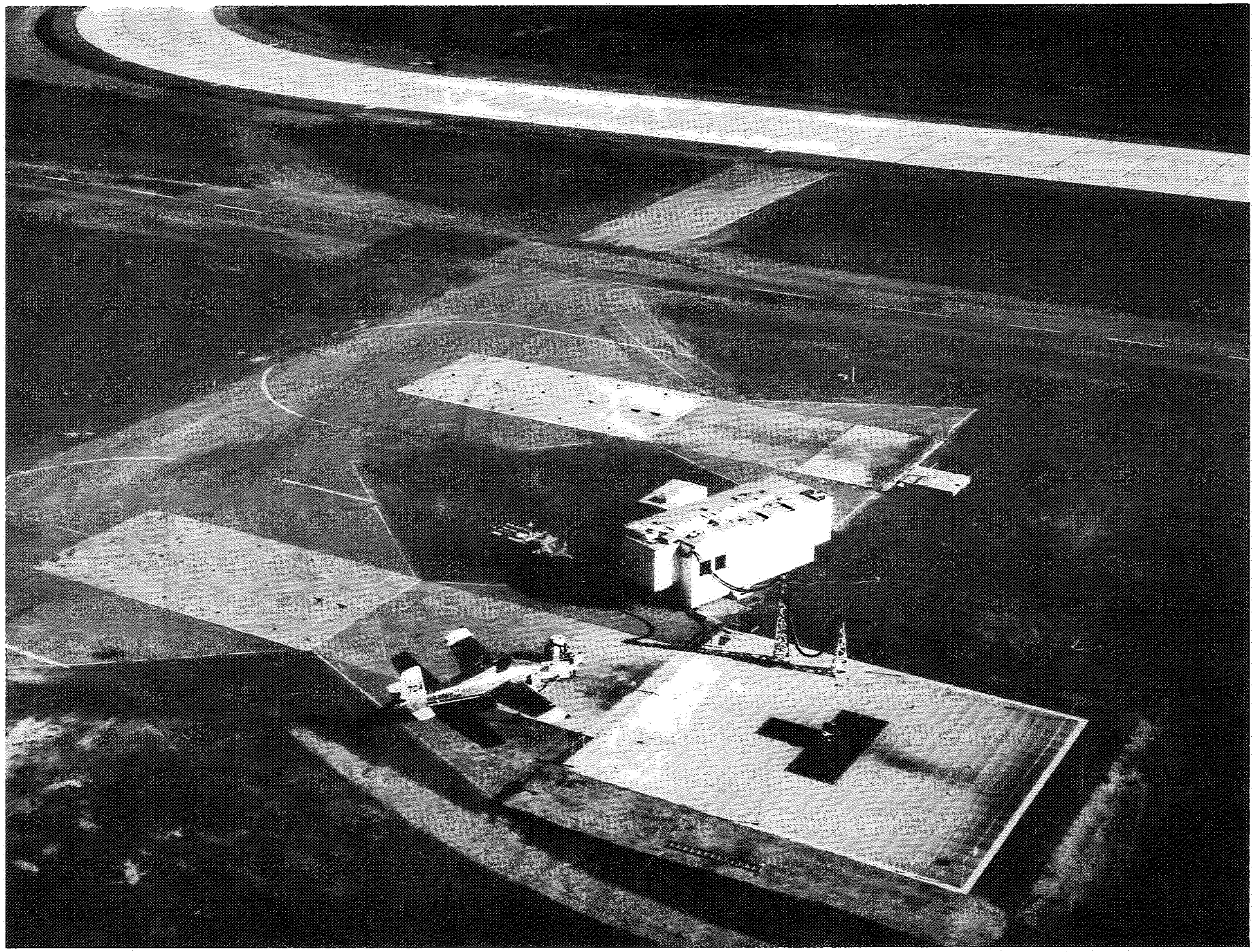


Figure 5. Aerial view of test stand.

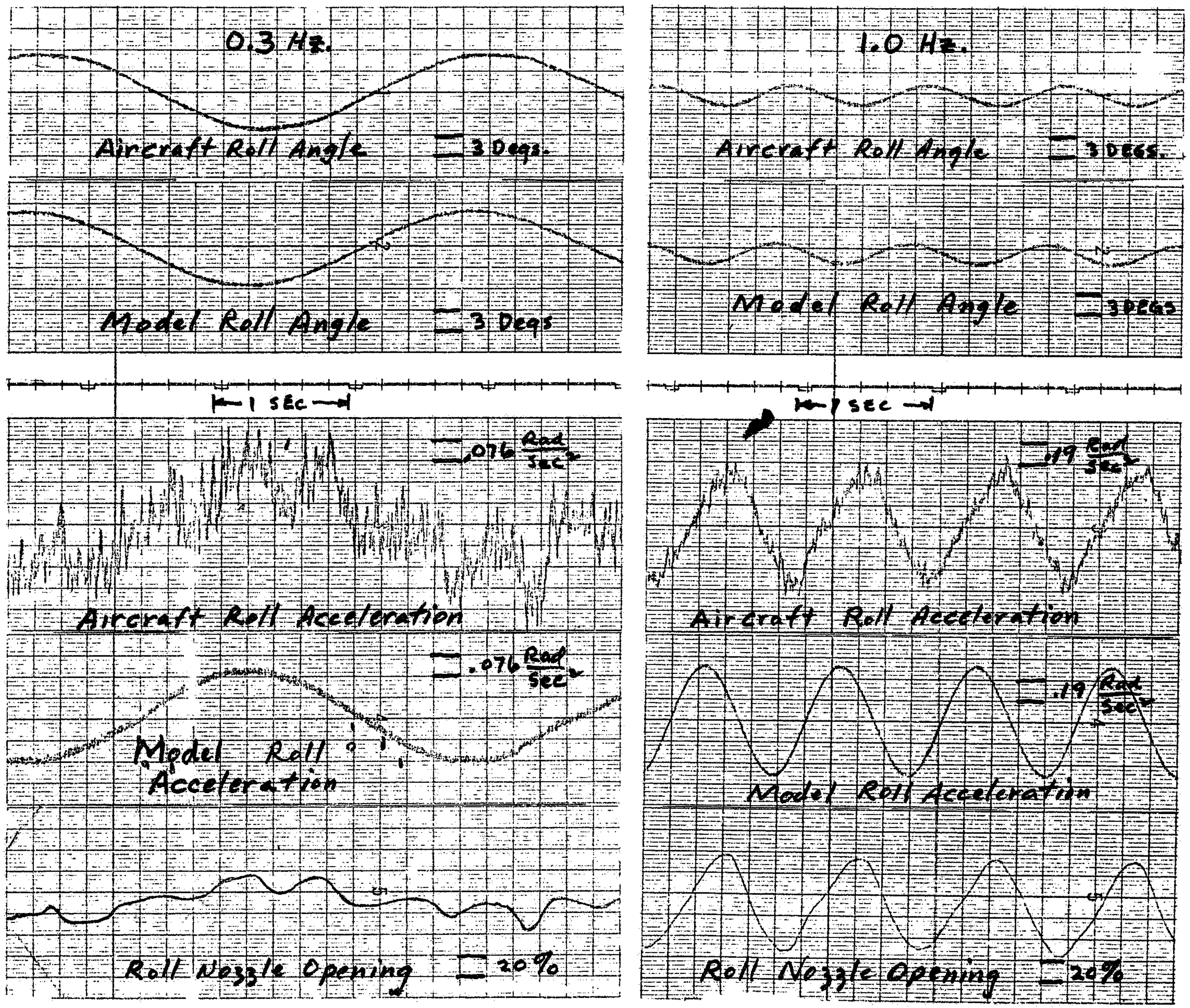


Figure 6. Frequency response data obtained in test stand operations.

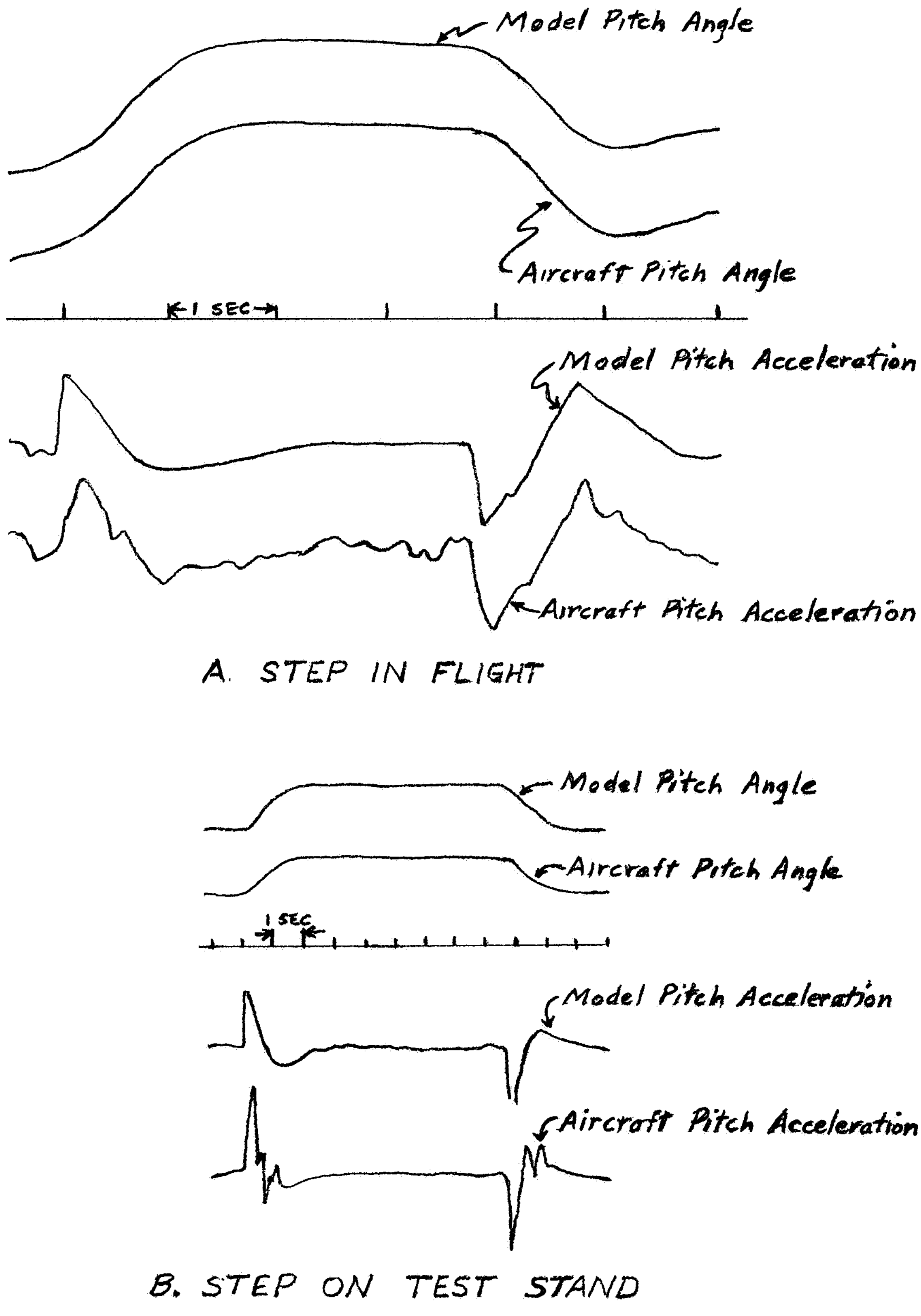


Figure 7. Comparison of step responses obtained on test stand and in flight.

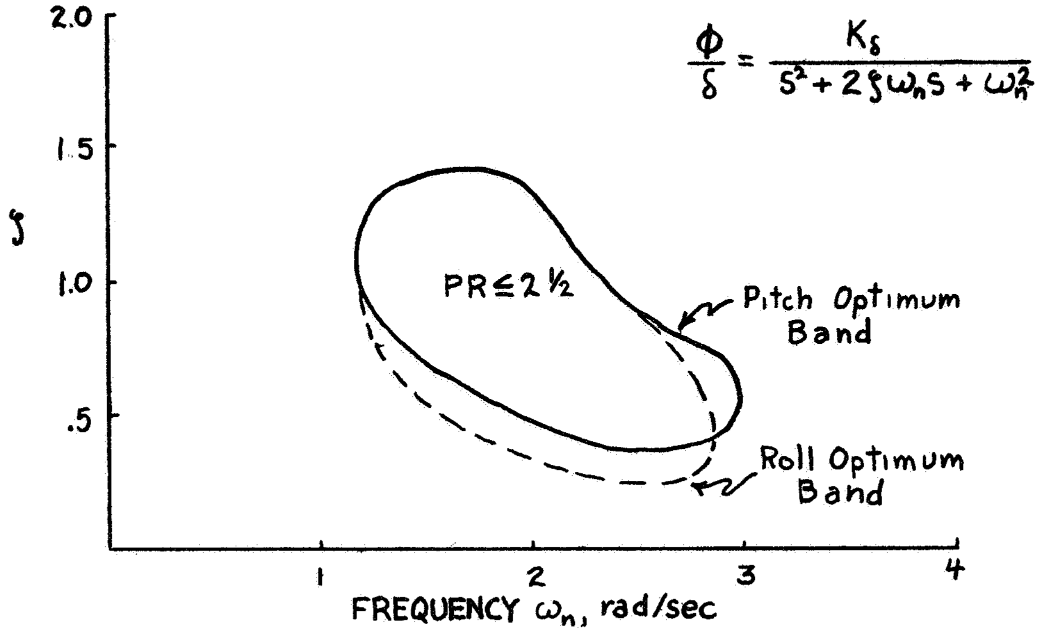


Figure 8a. Simulator results- attitude command system.

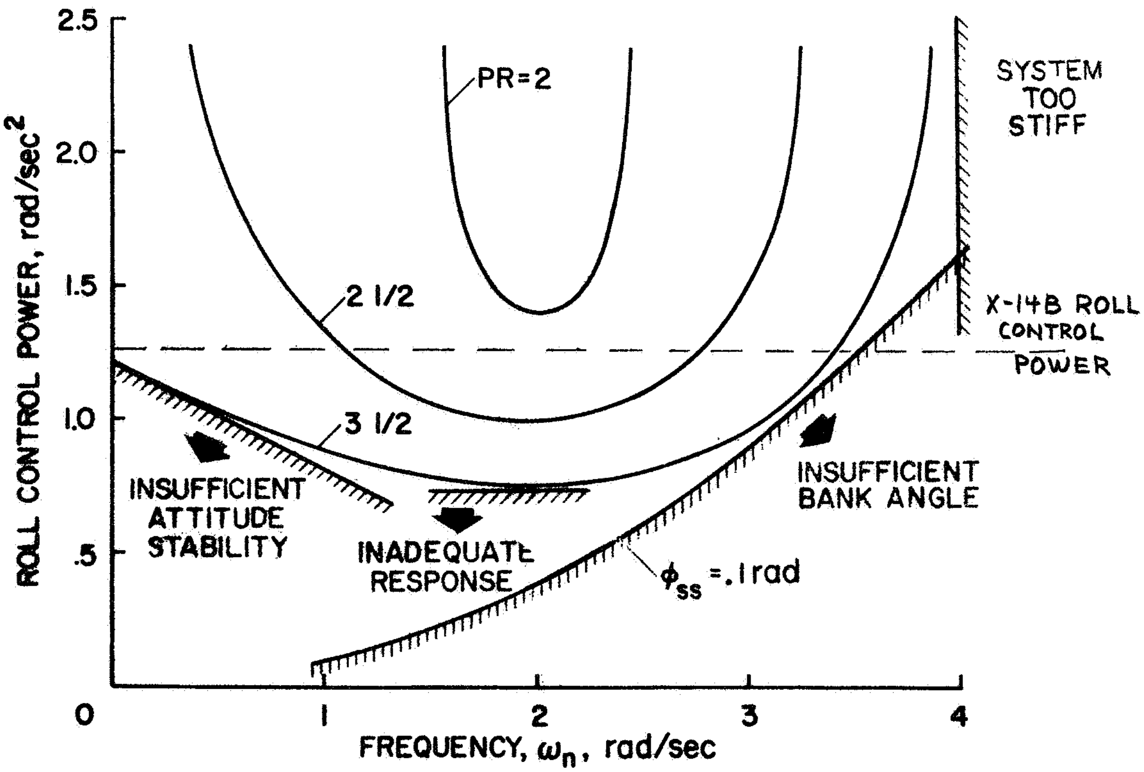


Figure 8b. Simulator results- control power effects on an optimized attitude command system.

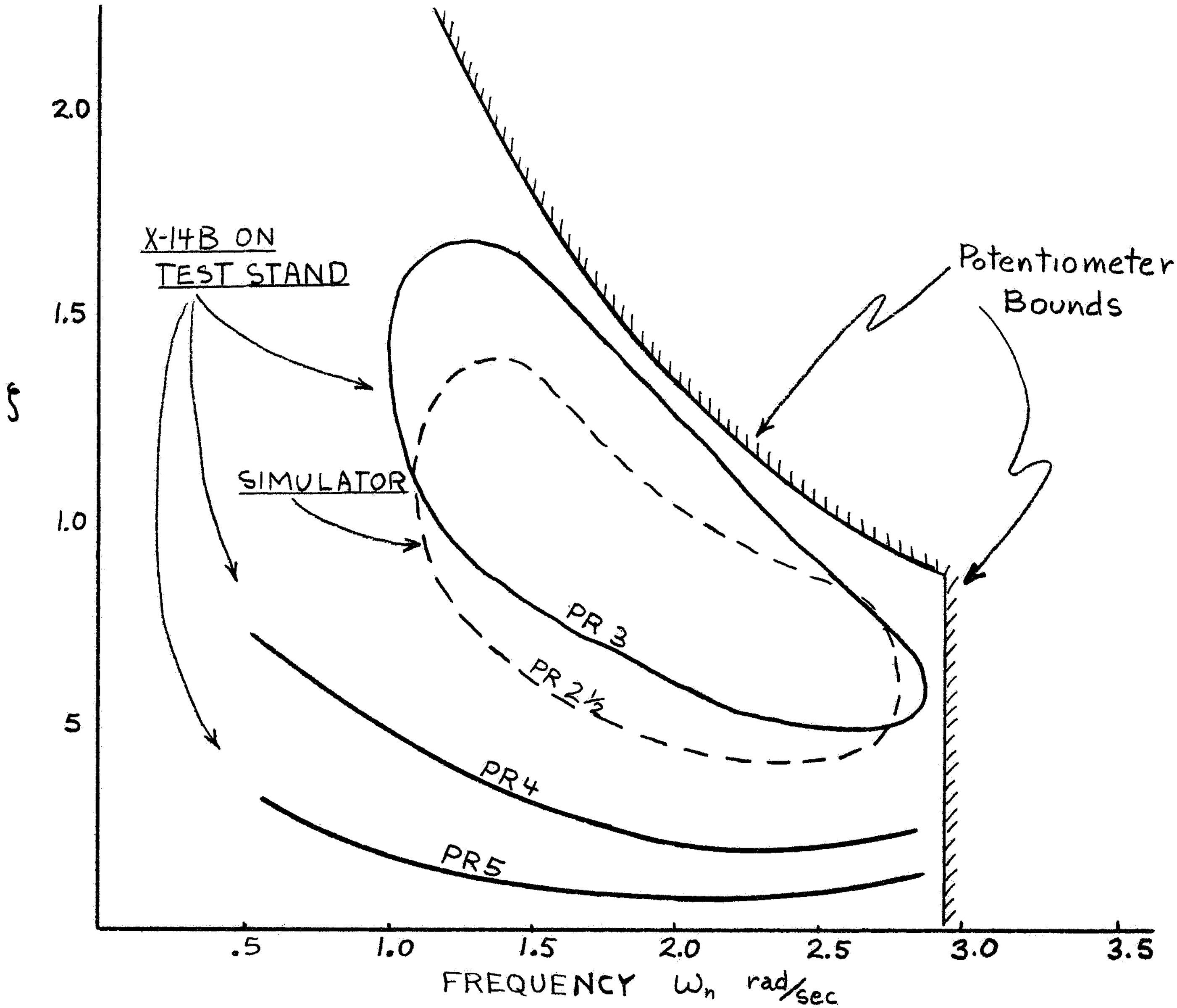


Figure 9. Direct mode (roll axis).

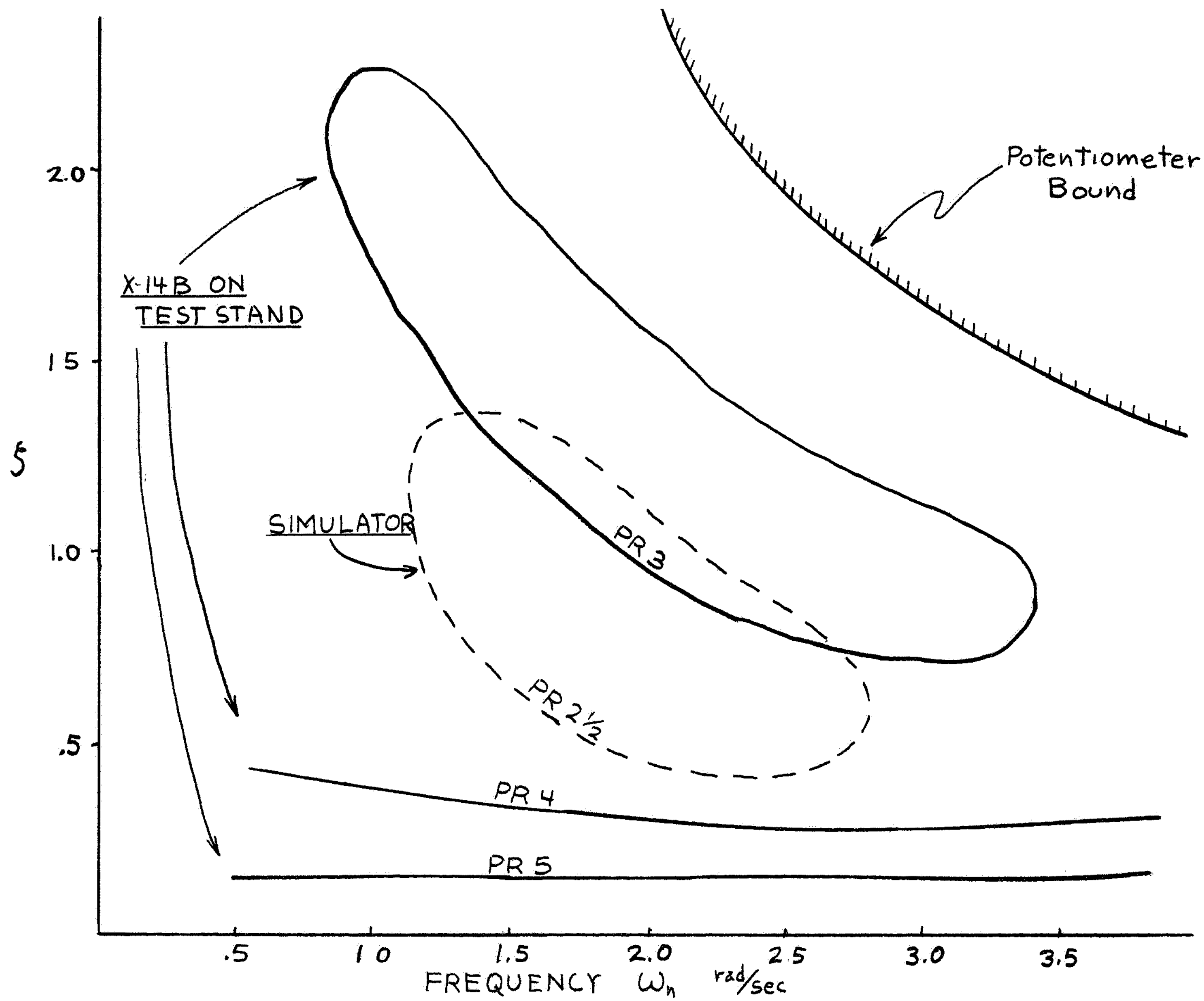


Figure 10. Model mode (roll axis).