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SHUTTLE REMOTE MANIPULATOR

SYSTEM HARDWARE TEST FACILITY

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ABSTRACT

The Shuttle Remote Manipulator (RMS) is designed and built for operations in a zero gravity environment. As such, the ground test facility for the integrated RMS must simulate conditions which will support verification of the overall system performance.

In order to allow ground test operations, a test facility was constructed with an area of 60 ft. x 120 ft. and extremely tight tolerances on floor flatness and slope. An air bearing support structure (Systems Test Rig - STR) was designed for the RMS to operate with 4 degrees of freedom.

This paper describes the RMS system test facility and systems tests conducted to date.

INTRODUCTION

The Space Shuttle Remote Manipulator (RMS) is an anthropomorphic, man-machine system primarily used for deploying and retrieving of payloads (satellites) in orbit. The National Research Council of Canada (NRCC) is funding the design, development, testing and evaluation of the first flight system. Detailed system requirements jointly formulated by NASA, NRCC and Spar Aerospace Limited, the prime contractor, define that the RMS shall be capable of deploying a 65,000 lb. payload and retrieving a 32,000 lbs. payload. The Manipulator Arm (MA) is 601 in. long and consists of a Shoulder (2 DOF), Elbow (1 DOF) and a Wrist (3 DOF) connected by upper and lower arm booms and a payload grappling device called the End Effector.(1)(2) The RMS system is illustrated in Figure 1.

Since the RMS is designed to operate in space environment, test and verification of expected performance require special facilities. In addition to ground tests, two simulation models are used to provide in depth analysis of performance under varying conditions.

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SYSTEM DESIGN DESCRIPTION

The RMS is comprised of four major subsystems:

(a) Mechanical Arm Subsystem
(b) Display and Control (D&C) Subsystem
(c) Electrical Subsystem
(d) Software Subsystem

Canada is responsible for the production of the first three subsystems and the requirements definition of the fourth. The software subsystem is implemented within the Orbiter General Purpose Computer (GPC) which provides automated and semi-automated control of the RMS.

Control of the RMS is provided by the D&C Subsystem. This subsystem contains a Display and Control Panel, Translational Hand Controller (THC) and Rotational Hand Controller (RHC). These provide the Orbiter crew with control of the Mechanical Arm.

The D&C Subsystem interfaces with the Manipulator Controller Interface Unit (MCIU) which in turn provides the interface to both the GPC and the Electrical Subsystem within the Manipulator Arm. Both the D&C Subsystem and the MCIU form part of the Orbiter cabin equipment. The Mechanical Arm contains the balance of the electrical subsystem which provides control of each of the degrees of freedom as well as the End Effector.

RMS PERFORMANCE EVALUATION PROCESS

The verification process of the RMS is undertaken through non-real-time and real-time simulation analysis component tests systems tests and orbital flight tests. Primary means of verification of overall performance prior to flight is through simulation and systems test. The benchmark simulation model of the RMS is the non-real-time model "ASAD". ASAD incorporates up to thirty selectable flexible modes and is used to provide complete confirmation regarding the dynamics of operation such as deployment and retrieval of payload singularity management, automatic trajectories and arm positioning capability.

In order to evaluate operator interaction with the RMS a real-time simulation facility "SIMFAC" is used. The SIMFAC model is based on ASAD but is restructured to permit real-time processing.(3)

The requirements for the RMS Systems Test Rig (STR) were established as part of the verification process of simulation, analysis and test. It was recognized that an attempt to perform a completely representative test on the RMS would be extremely complex and expensive. A trade-off study addressed the following global requirements:

(a) The exercise of a fully assembled RMS in a 1-g laboratory environment.

(b) Test two models; an Engineering Model (EM), and a Flight Model (FM).

(c) The verification RMS performance.

(d) Provide hardware performance data in support of the computer simulation programs.

The most complicated STR appeared to be a true three-dimensional rig and the simplest was a two dimensional horizontal plane rig. Construction of the system integration and test floor area was based on the probability that a single plane system would be required. A 60' x 120' area was provided. As a result of the initial studies conducted, it was determined that a system based on planar motions would provide the best overall compromise between cost, schedule and performance.

The following requirements were an outgrowth of the study and provided the design drivers for the STR:

(a) Provide a qualitative assessment of system operation.

(b) Verify or substantiate those elements of the Contract End Item Specification which could only be done by an integrated system test.

(c) Support development testing; Primary Design Drivers were:

i) Design to accommodate pitch and yaw coupled motions (serially).

ii) Accommodate arms with varying weights from 600 lbs. to 1,000 lbs.

iii) Friction .003.

iv) Failsafe such that any failure within the support system would not damage the RMS.

v) Accommodate the floor fluctuations up to .25 inches over 3 feet.

vi) Minimum interaction with mechanical arm dynamics.

vii) Permit joint to travel over the full operational range.

viii) Permit the arm to float on the STR such that dynamic or parasitic coupling from the STR would be minimized.

The requirements for payload operations in the integration area with the RMS were based on limitations that could be expected with a coefficient of friction of approximately .0025. The minimum force capability requirement from a straight arm is approximately 12 lbs. The maximum payload size that can be driven on air bearings would be in the order of 4,000 lbs.,

C-2

assuming 20% loss in torque capability of the arm due to STR friction. On the basis of information which would be gained from loaded arm tests, it was decided not to use a large mass payload for the Engineering Model arm tests and restrict operations to the unloaded arm with a low mass payload (50 lbs). This would permit evaluation of system stability during track and capture of a payload.

THE SYSTEMS TEST RIG

The STR is shown in Figure 2. The Shoulder joint is anchored on a fixed base (plinth). The shoulder can be attached to the plinth in either the pitch coupled or yaw coupled mode. The upper arm boom is supported at the shoulder and elbow interface flanges by the upper arm STR. This section provides a single 8" air bearing pad at the Shoulder interface and two 8" pads at the Elbow. Spacing between the Elbow pads is designed to counteract any pad flutter instability and any tendency to tip during arm acceleration or braking.

The lower arm is supported in the same manner at the upper arm Elbow flange and Wrist electronics compartment interface flange. One air pad is provided at the Elbow and two at the Wrist interface (Figure 3).

The Wrist and End Effector are supported on three air pads as shown in Figure 2 such that loading is balanced between the pads.

CRITICAL DESIGN AREAS OF THE STR

Since the STR is used to assess performance of flight hardware, undue loading of the system must be avoided. In order to meet this requirement, operational loads greater than 50% of the endurance limit must be avoided. Drivers to the design of the STR become:

(a) Joint Accelerations.
(b) Static and Dynamic Stability of the STR.
(c) Braking of the MA under normal and joint seizure conditions.
(d) Failure of the air supply or air bearing pads.
(e) Variations in floor slope and lift off of the air bearings.

In order to meet the static loads requirements with an arm stiffness of 10 lbs. per inch deflection of the End Effector, the allowable variation in support height at the Elbow and Wrist is ±0.10 inches. Since the total height variation could be as high as 0.5 inches due to air bearing lift off and floor variations, a support mechanism that accommodates these changes becomes essential. In order to meet these requirements a constant force device was chosen to interface between MA support flanges and the air bearing system.

THE PLINTH (Figure 2)

The plinth is a rigid support to which the Shoulder is attached. The mounting arrangement provide for the MA Shoulder vertical center line to be held either parallel or perpendicular to the floor (depending on whether the arm is in pitch coupled or yaw coupled mode.

In order to cater for the worst case failure of a Shoulder seizure at maximum arm rate, a torque limiting breakout clutch is incorporated between the plinth and the Shoulder interface. The clutch is designed to slip between 1,000 and 1,500 foot-pounds and is adjustable.

UPPER AND LOWER ARM SUPPORT MODULES

The configuration of the support modules is shown in Figure 3. Five point support is provided to the MA in order to meet arm stress load requirements. The three air bearing pads are provided on each module for static and dynamic stability.

The main structural member is a 6 inch diameter thin wall aluminum tube which also acts as a plenum for the air supply system. The plenum is used as an additional supply of air in the event of failure of the air supply system. Castors are also provided as a backup support system in the event of failure of the primary air bearing system.

WRIST AND END EFFECTOR SUPPORT MODULE

The Wrist and End Effector module duplicates the support mechanisms of the upper and lower arm sections. The air pads are displaced about the center of gravity of the support weight. The support flange location is chosen to minimize the static moments on all three of the wrist joints.

FLEXIBLE SUPPORT MECHANISM

The flexible support mechanism arrangement as shown in Figure 4 minimizes moment and torsion transfer to the MA support flange while maintaining the support force constant. Vertical motion of ±2 inches is provided. This motion is balanced by a beam linkage which acts against the constant force device.

The constant force device is a double spring system which provides for a "constant" reaction load over a prescribed linear movement by equating load moments with spring moments through a linkage system. A low spring rate is attained (1 pound/inch) at a nominal 150 pounds-feet. By providing adjustment of the lever ratio, a linear relationship is attained over ±10% variation of nominal load setting. Total load variation is less than ±2% over the full range of travel and ±1% over a ±2 inch travel.

Dynamic characteristics were measured for the linkage/constant force device over the velocity range of zero to 0.65 feet/second with a range of movement equivalent to 5 inches at the STP support paint. Test results indicated that, dynamically, the device operates within the ±2% load variation and showed no resonance conditions within the system bandwidth.

AIR BEARING SYSTEM

The air bearing system is based on an air pad of 8" diameter.

This pad was chosen on the basis of static and dynamic stability over the load range of 130 to 500 lbs. with a friction coefficient between 0.001 and 0.003.

Development testing indicated that the operating band of the air bearing system had a fairly narrow stability range as shown in Figure 5 and is sensitive to low load. In order to avoid this condition, each air pad incorporates its own separate plenum with the air supply entering through a choked nozzle. Because the main air supply is carried at a higher pressure than that of the pad operating pressure, failure of the air supply will cause gradual failure of each pad. Adequate time is therefore available to allow the control and safety system to sense a change in vertical displacement and initiate an orderly shutdown of the MA.

In order to evaluate the characteristics of the air bearing system a development setup was constructed consisting of three air pads, a static and dynamic load and safety castors. Tests were conducted on the task area floor which is made up of linoleum strips approximately three feet wide by 60 feet long.

Results of the friction tests verified the linoleum's friction coefficient of between .001 and .003. Static and dynamic friction are approximately identical since the internal fluid velocity is high compared with the imposed relative velocity between the bearing pad and the floor surface.

The relationship between drag force and support load was found to be essentially constant within the limits of intended load variation.

Tests were also conducted with a support load offset to simulate the effects of inertia forces causing an overturning moment about the air pads. To simulate the effect of floor slope, tests were carried out with pad slopes between 1 degree and 4 degrees relative to the floor. Results of these tests indicate that overturning moments and floor slopes which would be encountered would have negligible effect on the friction drag.

Measurement of pad liftoff was taken during the friction test. Liftoff was found to be 0.375 inches. Tests with the castors in place indicated that the pad would reinflate with 1/16" of clearance.

With a support weight load of 280 lbs. applied to the air pad the pressure and flow were set at 5.5 psig and 8.8 SCFM respectively. Tests over the entire floor surface produced a nominal friction of between 0.0015 and 0.002.

The total requirement based on stability requirements established the air supply requirement as 60 SCFM at 40 psig.

Tests indicated the natural frequency of the air pad system under unstable operation as 11.5 Hz @ 280 lbs. and 9.0 Hz @ 380 lbs. The system also indicated heavy damping with a peak amplitude of 0.05 inches.

MA/STR DYNAMICS ANALYSIS

The unloaded arm has a natural frequency of 0.5 Hz. Analysis using computer model and a total STR weight of 890 lbs. showed the first two natural frequencies to be 0.5 and 3.5 Hz. Laboratory tests indicated a natural frequency for an unloaded STR to be about 11 Hz. It is concluded that the two systems do not couple through the action of the small friction force passed through the constant force device.

CONTROL AND SAFETY SYSTEM

The control and safety console provides monitoring of the following.

(a) Supply air pressure.

(b) Floor clearance of each of the inflated air pads.

(c) Support loads at each of the five interface stations.

(d) Vertical support positions of the five interface stations.

(e) Plinth slip clutch.

Should any of the monitored status indicators fall outside prescribed limits, an alarm is sounded and the failure location is annunciated. A signal is also fed to the RMS control computer which brings the arm to rest. The signals also provide an interlock to ensure the MA cannot be functioned until the STR is in full operational status.

SETUP OF THE STR

Based on development test results for the air pads and constant forces devices the STR was set up prior to delivery. When tested on the flat floor, the only adjustments required were the height and level of the five arm interfaces. Dynamic tests with simulated loads applied to the five interfaces indicated no tendency towards instability as well and the load variation well within the ±2% limits.

ENGINEERING MODEL RMS SYSTEMS TESTS

Systems tests of the Engineering Model (EM) RMS occurred in late 1978 and during 1979. The setup is shown in Figure 6. A Hewlitt Packard HP21MX was used as the system computer with software which represented the orbiter RMS software. The EM MA differs from the flight model in that aluminum arm booms are used instead of the light weight graphite epoxy booms. Although the EM boom stiffness is representative of flight, there is an additional weight of approximately 300 pounds. The purpose of the EM systems test was to provide data in the following areas:

(a) System stability and controllability.

(b) Software/hardware compatibility.

(c) System stiffness.

(d) Operation in the different control modes.

(e) Payload operations limited to the use of a small dolly.

(f) Stopping distance from maximum rate.

(g) Maximum tip force.

Initial tests conducted driving the Shoulder showed the STR friction to be about 122 foot-pounds; well within design predictions. Examination of joint motor current traces were used for evaluation of floor slope and fluctuation. Again, the floor showed minimal effects on overall system performance. Track and capture tasks were performed using a commercial television system with the small payload drawn along the floor at typical payload rates. Operators familiar with SIMFAC simulations were used for the above tasks. Generally, the operators felt that the EM system tended to show more damping and less amplitude excursions during step inputs. Part of this is believed to be caused by the loss of the cross axis degrees of freedom and flexibility but generally the system performed well within the anticipated performance domain.

Another test conducted was to command the arm at very low rates in a straight trajectory. Results indicated that an End Effector rate of approximately 0.035 feet/second could be attained. This is very close to the lower limit of the design capability and indicates excellent characteristics of floor slope and waviness as well as action of the air bearings and constant force devices. Deviations from the straight line trajectory were approximately 4 inches in 20 feet. Based on a specified joint rate accuracy of ±0.7 radians/second at the motor and taking into effect the expected floor friction, the results were well within specification.

A comparison run was made between the simulation program ASAD and the RMS. The typical plot of results for the shoulder and elbow pitch joints is shown in Figure 7. As a general observation the EM arm appears to follow the input commands more closely than the ASAD program in spite of the higher EM arm inertia (factor-of two higher).

CONCLUSION

Results of Engineering Model system tests of the RMS have indicated that the system test facility has exceeded expectations in the use for evaluating performance of the RMS in a zero -g environment. As a result, more rigorous testing will be performed on the flight model than had been originally planned. Also, tests using a payload for evaluation of partially and fully constrained motions will be performed. This gives confidence in the RMS abilities to deploy and stow payloads in the orbiter retention system prior to the use of the Payload Deployment and Retrieval System in flight.

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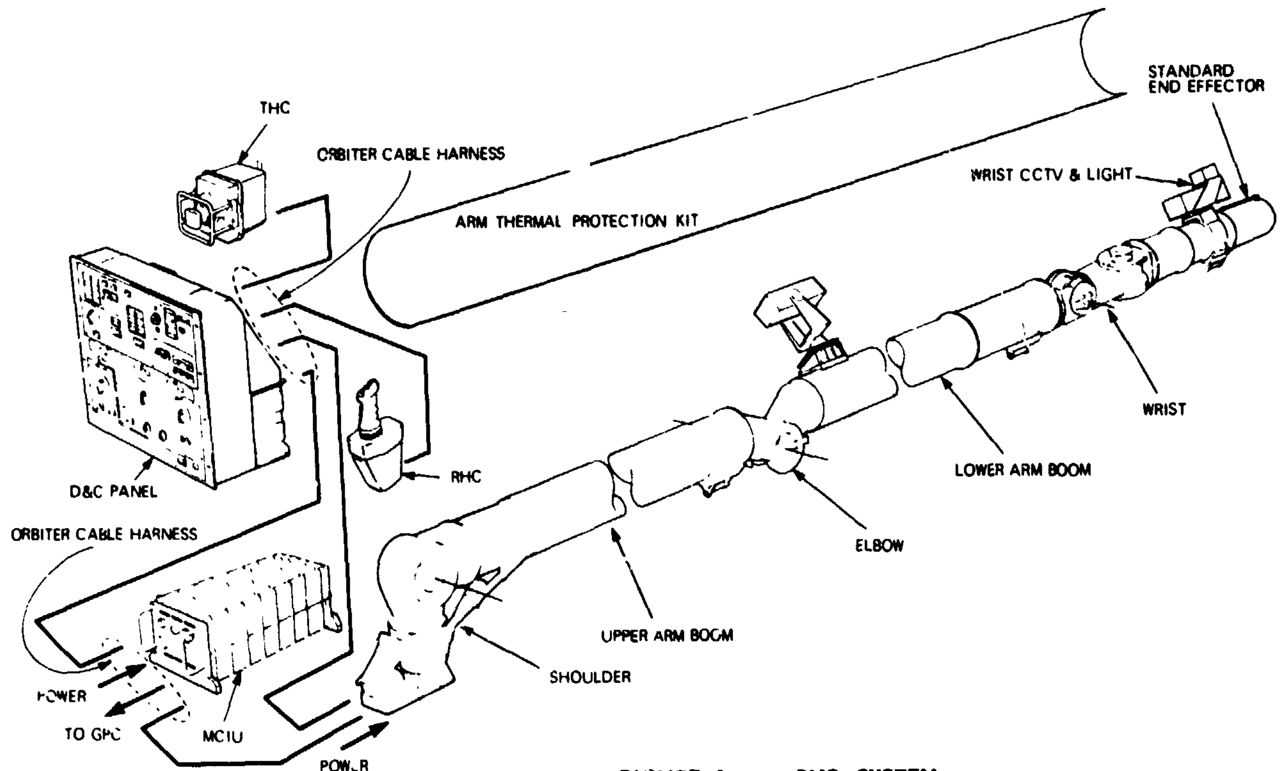

FIGURE 1 RMS SYSTEM

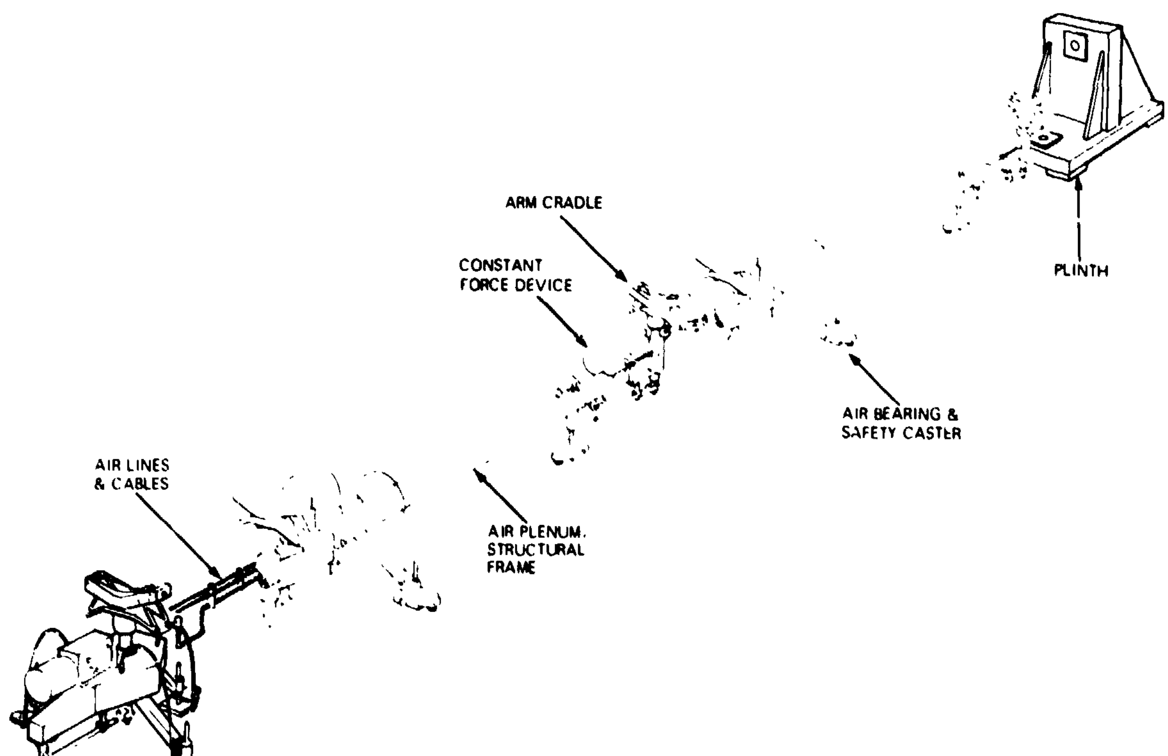

FIGURE 2 SYSTEM TEST RIG

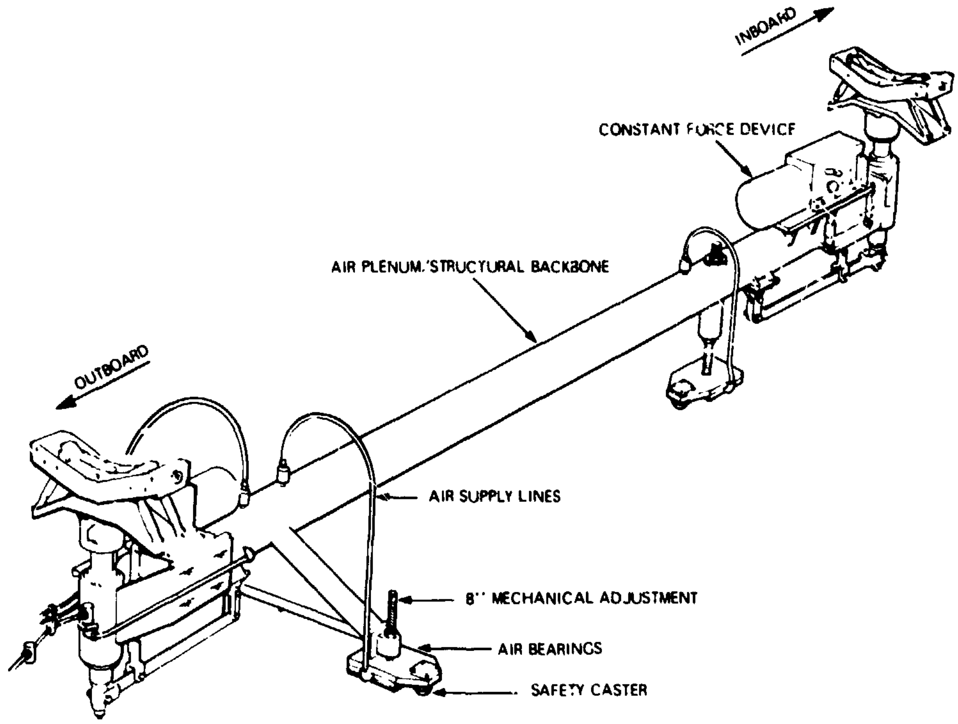

FIGURE 3 SYSTEM TEST RIG LOWER RMS ARM SUPPORT

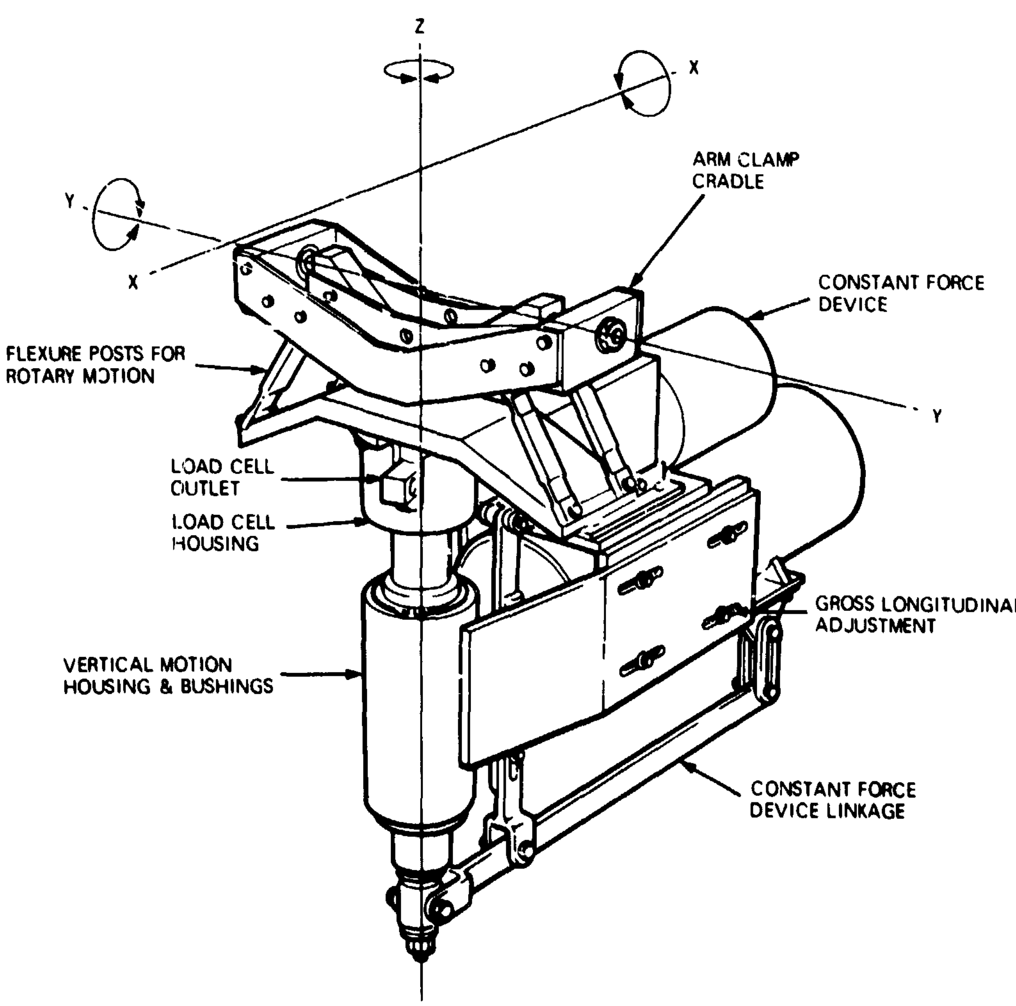

FIGURE 4 FLEXIBLE SUPPORT MECHANISM

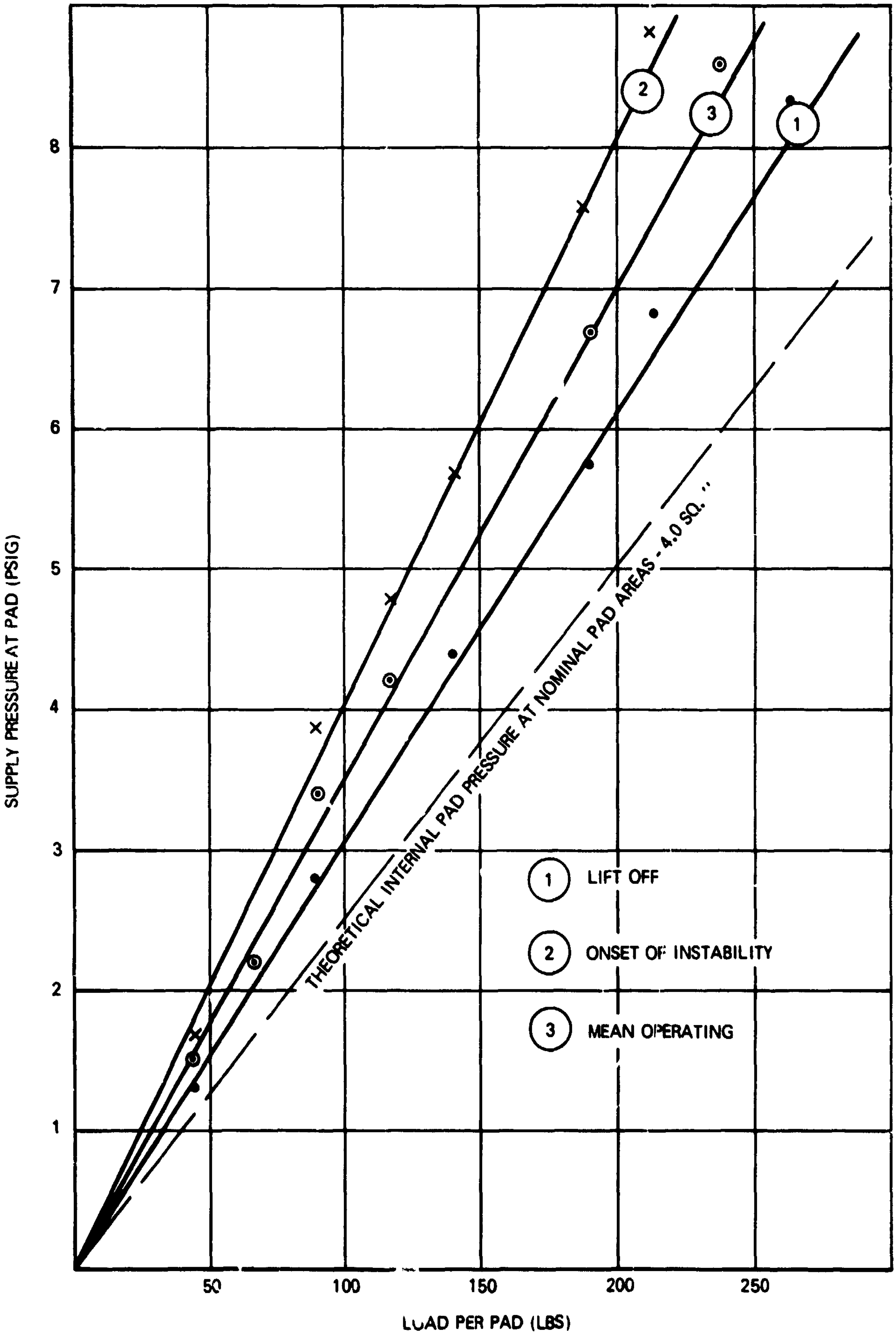

FIGURE 5 8'' NOMINAL DIAMETER PAD

FIGURE 6 MOUNTED SYSTEM TEST RIG DURING SIMULATED PAYLOAD TRACK & CAPTURE

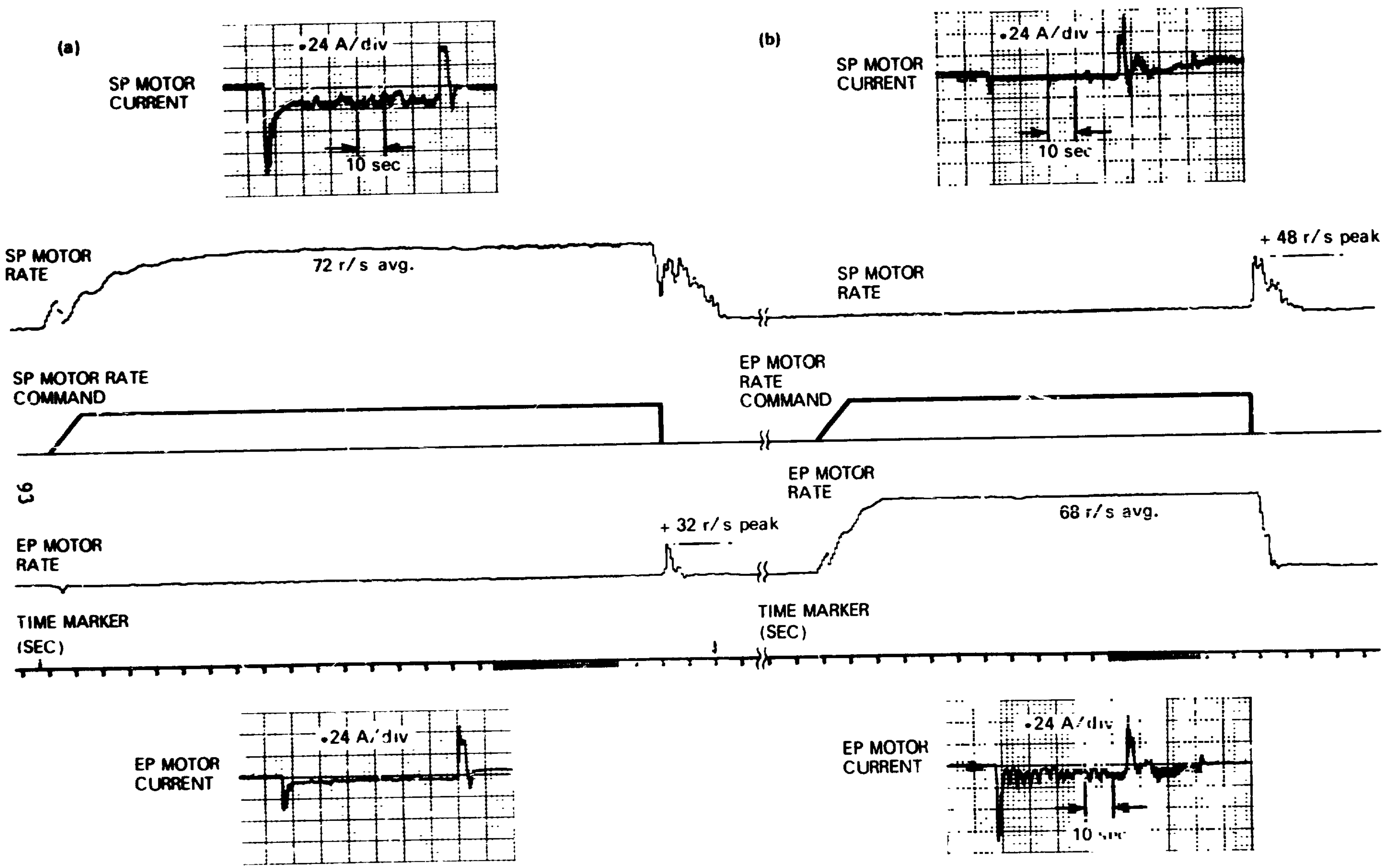

FIGURE 7 SINGLE JOINT MODE: (a) SHOULDER PITCH COMMAND (b) ELBOW PITCH COMMAND (EXTENDED ARM)