Design and Test of Electromechanical Actuators for Thrust Vector Control

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ABSTRACT

New control mechanisms technologies are currently being explored to provide alternatives to hydraulic thrust vector control (TVC) actuation systems. For many years engineers have been encouraging the investigation of electromechanical actuators (EMA) to take the place of hydraulics for spacecraft control/gimballing systems. The rationale is to deliver a lighter, cleaner, safer, more easily maintained, as well as energy efficient space vehicle. In light of this continued concern to improve the TVC system, the Propulsion Laboratory at the NASA George C. Marshall Space Flight Center (MSFC) is involved in a program to develop electromechanical actuators for the purpose of testing and TVC system implementation. Through this effort, an electromechanical thrust vector control actuator has been designed and assembled. The design consists of the following major components: Two three-phase brushless dc motors, a two pass gear reduction system, and a roller screw, which converts rotational input into linear output. System control is provided by a solid-state electronic controller and power supply. A pair of resolvers and associated electronics deliver position feedback to the controller such that precise positioning is achieved. Testing and evaluation is currently in progress. Goals focus on performance comparisons between EMAs and similar hydraulic systems.

INTRODUCTION

Recent studies have shown that hydraulic actuation systems cost the space program many valuable hours for tests, maintenance, and repairs. During the typical turnaround cycle for a space shuttle orbiter and its integrated systems, many maintenance personnel inspect the entire vehicle, repairing hydraulic leaks and examining lines, while at the same time qualifying each hydraulic unit for its next flight. Qualification alone necessitates extensive hours, or about 10 per cent of the total inspection time. Estimates submit that fully electric orbiters could possibly be readied for flight ten days earlier than hydraulic ones. These problems affecting mission readiness have prompted investigations by NASA into alternate actuation systems for use in existing space applications, as well as new programs soliciting heavy lift TVC technology. Some reservations of implementing electric TVC systems into these very new programs overshadow the fact that EMAs have been in service for more than thirty years. A good example of an early EMA technology application is the Redstone Missile in the 1950's. In this system, an electrical chain drive actuated air fins for aerodynamic steering. As early as 1972, NASA engineers expressed concern over the space shuttle's hydraulic system due to difficult maintainability and some minor inefficiencies. In the last few years, many advances in the fields of power electronics and motor technology have renewed interest in the use of EMAs for both low and high power actuation in space applications. In 1987, the Control Mechanisms and Propellant Delivery Branch at MSFC designed and tested an electromechanical propellant valve actuator applicable to the space shuttle main engine. It performed as well as, and in some areas better than its hydraulic counterpart. Therefore, realizing the potential what this new science can provide for space vehicle actuation systems, MSFC has undertaken this project to explore the full potential of EMAs. After fine tuning of the hardware and system, implementation of a family of EMAs designed for use in multiple applications will follow.

DESIGN

The electromechanical thrust vector control (EMTVC) actuator was designed to meet basic loading requirements necessary to support future heavy lift space vehicles. These requirements are given in Table 1. The primary mechanical components of an EMTVC actuator can be seen in Figure 1. These components are, 1) some type of electric motor, 2) if needed, a gear train, and 3) a linear screw. Figure 2 shows an assembly drawing of the EMTVC.

Table 1. Basic Design Requirements

Dynamic Load Capacity: 35,000 lb
Linear Velocity: 5 in/sec
Maximum Stroke: +/- 6 in
Control: Two Channel Redundant
Bandwidth: >3.0 Hz
Linearity: < 2%
Accuracy: < 0.050 inch

I. Motors

Several types of motors were considered for this application. Through careful deliberation and various trade studies, three-phase, permanent magnet (PM), brushless, direct current (DC) motors containing a large number of poles were chosen. A fundamentally sound design and combined overall characteristics helped finalize this choice. PM, brushless motors have high torque-to-weight ratios and high torque capability at low speeds. They are able to operate at high speeds with moderately linear output (torque versus speed) curves. The most significant feature of the brushless PM motor that proves most beneficial to the actuator is its ability to integrate into a redundant single shaft system. In this arrangement, a shorted winding proves to be less of a problem than would be expected. A shorted winding in a redundant electric motor system forces the fully operational motor to overcome drag torque produced by the failed motor. To overcome this drag torque, or generator effect, requires extreme overdesign in motor sizing unless a type of clutching device is used to separate the systems. Figure 3 shows important data necessary to the design of the entire motor scheme. As can be seen by the curve, at higher speeds drag torque decreases sharply. This decrease in drag torque occurs due to the multiplicative property that signal frequency has upon the inductive element in an electric motor. More poles in the motor make available a larger reactive component of the impedence, which increases the total impedence. Thus, a smaller current through the motor winding is created and, therefore, less power to cause drag on the system. Others have done work using this theory and have proven it with credible results.

Characteristics of the motor used are:

- Type: Three-phase brushless dc
- No Load Speed: 9300 RPM @ 270 volts
- Torque Constant: 34.6 oz-in/amp
- Back EMF Constant: 25.6 v/1000 rpm
- Dimensions: 5.50 inch O.D.
  x 5.045 inch length
- Weight: 17 lb

II. Gear System

To satisfy linear velocity requirements, a speed reduction is needed to the output shaft of approximately 9:1. The two pass gear system utilizes a design such that backlash is nearly eliminated (Figure 4). Spur gears transmit high torques necessary to drive the system in either direction. A two piece idler shaft/gear allows for on assembly adjustment to aid in minimizing rotational play. Characteristics of the gear system are shown below:

- Type of Gearing: Spur
- Teeth: Involute, 20 deg
- Face Width: 0.50 in. (1st pass)
  0.75 in. (2nd pass)
- Material: Steel alloy 8620
- Lubricant: Molybdenum disulfide Grease

Internal gear stresses and tooth contact stresses were calculated, which directly affected structural sizing of the gears.

III. Linear Screw

Rotational motion is converted to linear motion using a roller screw. Roller screws are high efficiency linear devices which provide a robust means of transmitting very high loads with considerable accuracy. They consist of a threaded screw shaft and a nut which houses contacting rolling elements (Figure 5). Triangular threads, with an included angle of 90 degrees, are machined onto the main screw shaft. Thread pitch may range from 0.015 inch to as much as 1.250 inches with 4, 5, or 6 starts. The rollers housed in the nut are machined with a single start triangular thread. Contact is made between the nut and shaft by the rollers. A barrelled thread form provides a large contact radius for high load carrying capacity and rigidity.

Two critical areas of highest concern were:

1) Dynamic load capacity for the given geometric envelope
2) Shock load capability

The Dynamic load rating in an application depends on the type and magnitude of the load applied, and the life of the screw in millions of revolutions. In a TVC system, the maximum dynamic load is only experienced at very short intervals during a flight. This characteristic duty cycle aids in compacting the actuators' geometry which, of course, is much to the advantage of the overall system design. Extreme shock loads and adverse environments may also be encountered on a mission. Transient shocks much larger than those loads experienced under normal continuous operation may be experienced by a TVC actuator at engine start up. Documentation shows that roller screws are best suited for these conditions. Data for the roller screw used are as follows:

- Material: Shaft - 4140, Nut - 52100
- Lead: 0.40 inches/rev
- Shaft Dia: 1.89 inches
- Lubrication: Molybdenum disulfide Grease

Other linear actuation devices were considered for this application, although none proved as worthy, based on all literature and performance data, as the roller screw.

IV. Electronic Controller

The Control Electronics Branch of the Information and Electronics Systems Laboratory was responsible for the design and fabrication of the analog controller (270V, 100A, 27kW) for the TVC actuator system. A switching regulator in the controller pulse width modulates (PWM) the 270 volt power source (currently provided by a battery bank). The modulated source is then passed through a coupling inductor to provide current for a three-phase, six transistor, six step, bridge network. The six transistors in this network aided by two additional transistors used in the PWM process, as well as the regenerative circuitry are insulated gate bipolar transistors (IGBT) rated at 500V, 200A. This bridge assembly provides the correct commutation of current to the motor windings. Synchronization is achieved by utilizing output applied to the commutation logic from motor Hall Effect devices. This logic also protects the circuit by ensuring that both transistors of a phase are not turned on simultaneously. Current is sensed out of the inductor by a separate Hall Effect device for current feedback to the controller. Position feedback is provided by the resolver at the output of the gear train. This signal is then compensated for the difference between measured position and the actuator position (at the output of the roller screw) before it is used for feedback to the controller. For redundancy purposes, a controller for each motor will be built.

TESTING

I. Facility

A rigorous testing program is currently under way in a full scale hydraulic test facility at MSFC. Component and subsystem development from concept through flight qualification can be performed. This facility, originally constructed for Apollo and Space Shuttle TVC systems, contains operational test facilities such as fluid pumping systems, flow test benches, static load application test fixtures, and dynamic inertia simulators which are fully supported by instrumentation, data acquisition, and analysis equipment. Data acquisition equipment used for all tests consisted of a 200 Hz, 12 bit, 8 channel computer operated system. Data analysis was performed using MATLAB based program.

This facility will allow comparisons to be made of the EMA to similar hydraulic provisions. A broad spectrum of capabilities are available.

Fluid power requirements for the entire facility are provided by several pumping systems. Two large units, when combined, have a flow capability of 800 gal/min at 5000 psig. Four small pumps provide fluid power to the smaller test fixtures. These units, rated 30 gal/min at 3500 psig, may be combined to supply 120 gal/min total capacity. A separate pumping network rated 15 gal/min at an operating pressure of 8000 psig supports a high pressure prototype system.

Hydraulic flow benches deliver directional flow and operational control to various test panels. Fluid manifolds and test blocks are available to interface with all standard servovalve and high flow deflector jet types. Pressure can be regulated from start-up to full system capacity. Flow and pressure instrumentation is available in real-time.

A dynamic load simulator (Figure 6), originally configured to simulate structural compliance, inertia, and mounting provisions for the TVC system on the Solid Rocket Booster (SRB) of the Space Shuttle facilitates testing of the EMA. Tests such as frequency response, stability, and step response are discussed in more detail in the next section.

Load stand characteristics are:
Pendulum mass: 5000 lbm
Moment arm: 65 in
Dynamic spring rate: 140 Klb/in
Power: 27 kw

II. Testing Scheme/Results

The first phase of testing has been completed. Data analysis for this series of tests was performed and documented and will be used to update mathematical models of the system. Tests include step response, discrete sine dwells, frequency sweep response, and linearity. In addition, actual flight duty cycles were performed by the EMA and hydraulic systems. These tests determined the performance parameters of the actuator for comparison against design parameters. All design parameters were verified with the exception of piston rate under maximum load. Rate-vs-Load tests were omitted due to inadequacies encountered with the load fixtures. These tests will be performed during the second phase of the testing program.

All tests were executed at full power (270V, 100A) and are summarized below. Peak power reached 33.75 kW when the current spiked to 125 amps. Five channels of data were acquired relating the following: command signal, actuator position, load position, motor current, and supply current.

Figure 7 shows a plot of the frequency response of the actuator. The envelope around the data exhibits the current SSME requirement. The bandwidth is 4 Hz with 20-25 degrees of phase lag at 1 Hz (an SSME requirement). Resonance with the load structure occurs between 8 and 9 Hz. The peak in response magnitude corresponds to a critical damping ratio between 0.5 and 0.6. Figure 8 shows both a small and large excursion step response. The small step (0.25 inches) falls within the requirement envelope of SSME specifications. A 15 percent overshoot is seen. Data from the large step (5.0 inches) demonstrates that the actuator exceeds the design requirement velocity of 5 in/sec, and is actually capable of 6.8 in/sec under inertia load. The overshoot corresponding to the large step is approximately 14 percent. Overshoot associated with these step responses relate to the damping ratio determined by the frequency response. During the next phase of testing, a piston velocity of 5 in/sec will be verified with the actuator under rated load. Linearity tests on the actuator produced excellent results. Position data for a large excursion (5.0 inches) resulted in an error less than 0.030 inch which exceeds the 0.050 inch requirement.

Both linearity and position error data may be seen in Figure 9. The position error for the small excursion was below the noise level of the data. For an initial comparison between the hydraulic and EMA systems, an actual STS flight profile was commanded to the actuator. Response to the STS-44 SRB command profile may be seen in Figure 10. Actuator position response error in relation to the command signal is shown in the bottom plot. Note though, that while the EMA showed less error than the hydraulic unit, the test was run on the inertia simulator only and lacked the flight loads the hydraulic unit experienced. The capability to apply flight type loads for testing purposes is included in future plans for the test facility.

Since this testing was performed, a new single pass gear system has been designed for the actuator. A rate loop has also been added and is now undergoing tuning such that all design parameters are accomodated. Following the completion of this task, an additional test series will be run. Testing the actuator in a redundant configuration will be the next milestone. These tests will prove helpful in future redundancy studies as well as the introduction of Vehicle Health Management (VHM) to these systems.

SECOND GENERATION EMA

A second generation high power EMTVC actuator has been designed and is currently being assembled at NASA, MSFC. This actuator incorporates features that will increase performance, reduce weight, and provide a more compact package than that of the first generation discussed earlier. The primary mechanical scheme of both actuators are relatively the same, yet the second generation EMA utilizes features that enhance the entire component design. This actuator also incorporates length, stroke, and power capabilities required to support TVC system testing for heavy lift vehicles.

Basic Design Requirements:

o Dynamic Load Capacity: 45,000 lb
o Null Length: 47.330 inches
o Maximum Stroke: +/- 6 in
o Control: Four Channel Redundant
o Linear Velocity: 5 in/sec
o Bandwidth: > 4.2 Hz

Four high speed low inertia motors configured in a torque summing arrangement power the system. Since inertia is a major concern due to the EMA's nature of operation, optimization of horsepower, RPM, and motor rotor diameter is imperative. The amount of inertia seen by the controller governs the power required for each cycle of the actuator. Calculations show that the amount of inertia created by the rest of the system is essentially negligible when compared to the inertia created by the cyclic action of each rotor inertia.

The motors deliver torque to a single pass gear reduction system. The gear system transmits the necessary torque to a roller screw shaft which has been hollowed to decrease inertia. Torque to the roller screw shaft is converted to linear movements by the roller screw nut. As the nut moves, precise gimbal outputs are translated to the output piston.

A small harmonic drive (Figure 11) has been added to aid in position control. It provides a reduction mechanism such that the moving resolver race will not rotate greater than 360 degrees.

High strength aluminum (7075) is used in more parts to reduce overall weight. Figure 12 shows the second generation EMA conception. Component specifications are shown in Table 2.

Table 2. Component specifications

Motors:

o Type: Three phase DC brushless permanent magnet
o No load speed: 20,000 RPM @ 230 volts
o Torque constant: 16.8 oz-in/amp
o Back EMF constant: 13.8v/1000 RPM
o Dimensions: length-9.875 in
  dia-2.380 in
o Weight: Approx. 6 lb

Gearing:

o Type of gears: spur
o Teeth: Involute, 20 deg
o Face width: .625 in
o Material: Steel alloy 8620
o Lubricant: Dry film

Linear Screw: (same specifications as 1st generation EMA discussed earlier)

CONCLUSION

Conclusive system data concerning the EMA is forthcoming. Final testing goals will soon be fulfilled for this phase of MSFC's EMA program. These results are expected to supply greater confidence in the capabilities of EMTVC systems for future comparisons to hydraulic equivalents.

Following the final phase of testing, the 25 hp EM actuator will be shipped to Kennedy Space Center, Florida, where it will be used to familiarize personnel with operational issues associated with EM TVC systems. Design changes are being incorporated into the gear train and motors to better suit data criteria and EMA performance. Problem issues arising from the operations area may then be taken into account and incorporated into future actuator requirements and designs. Using information gained from experience with the first generation prototype EMA, MSFC will utilize the second generation, 4-motor, 45 hp EMA to further provide insight into topics such as load sharing (between channels), full redundancy implementation, and start transient load capabilities. MSFC test facilities will undergo upgrading to support this effort with additions of flight programmable loads to the inertia simulators, a possible VHM test platform, and other modifications to existing facilities to better handle specific requirements associated with the EMA. After the completion of extensive component testing, the actuator will undergo Technology Test Bed (TTB) qualification . TTB data will include vibration analysis, EMI/EMC, as well as thermal, shock, and acoustic information. The TTB hot fire tests will support the NASA Electrical Actuation Technology Bridging program.

NASA, MSFC plans to investigate all avenues of this technology such that optimization is accomplished. Upcoming EMA designs will aid in establishing a continued learning process to integrate test data and hardware for development of a proven EMTVC system.

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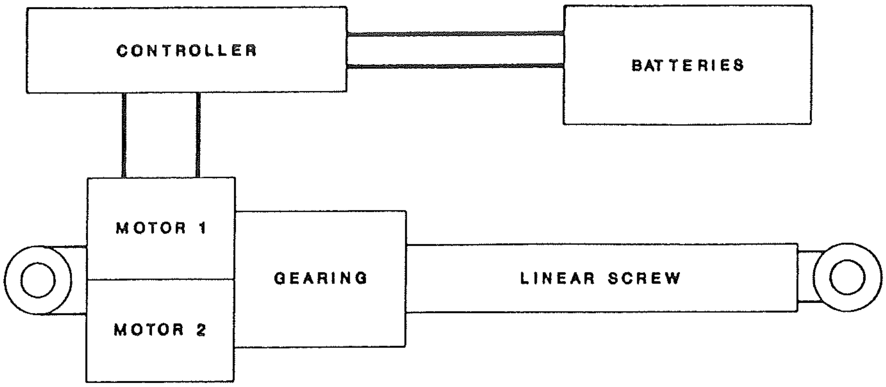


Figure 1. Basic EMA Schematic

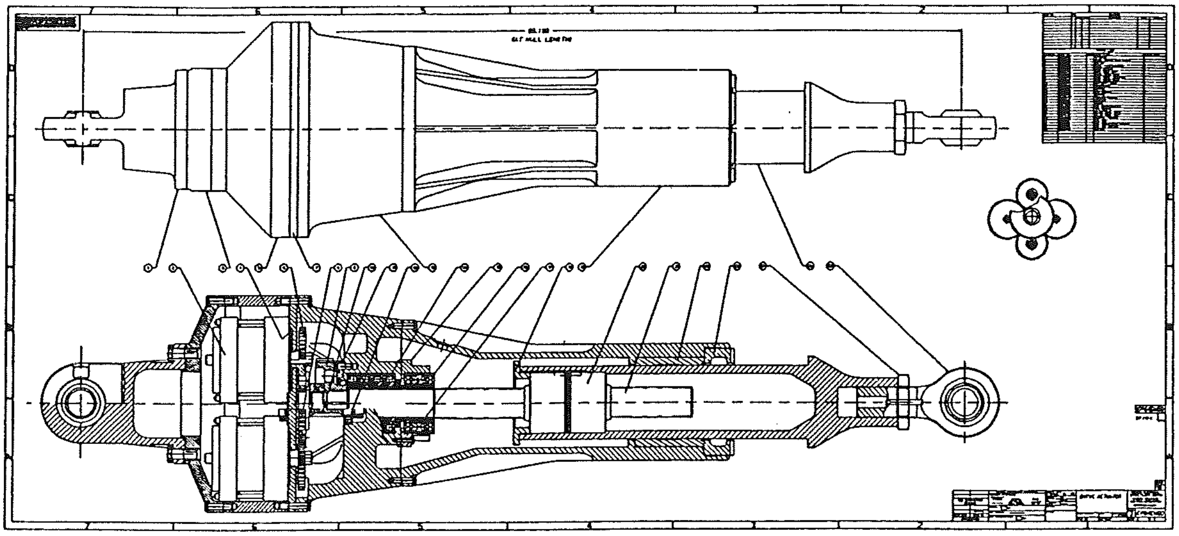


Figure 2. EMA Assembly Drawing

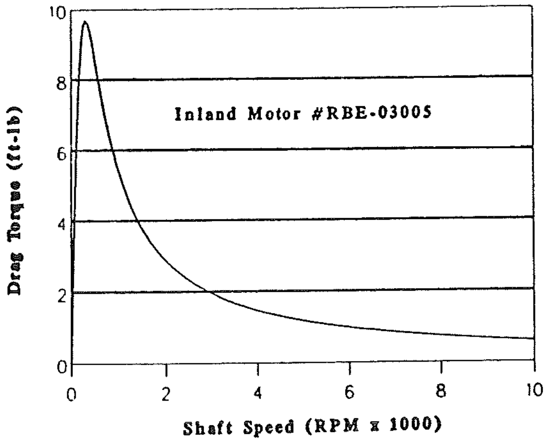


Figure 3. Motor Drag Torque-vs-RPM

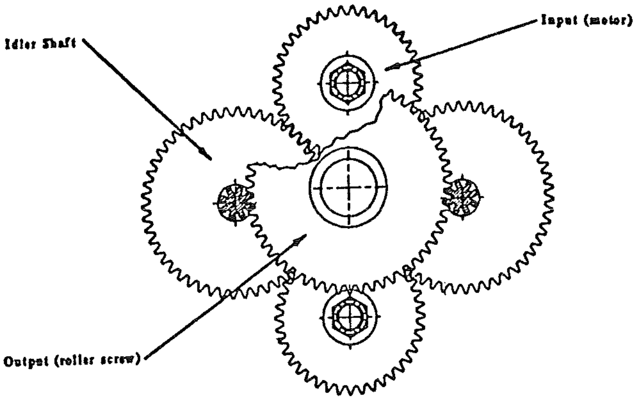


Figure 4. View of Gear Arrangement

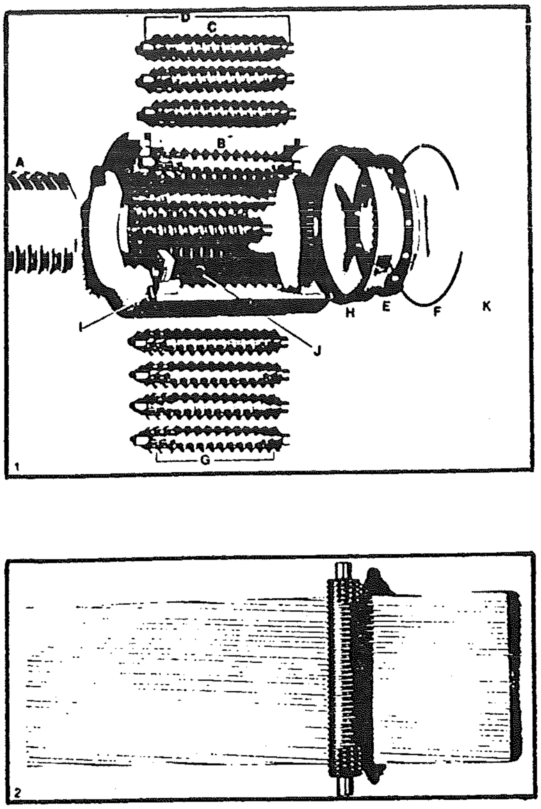


Figure 5. SKF Linear Roller Screw

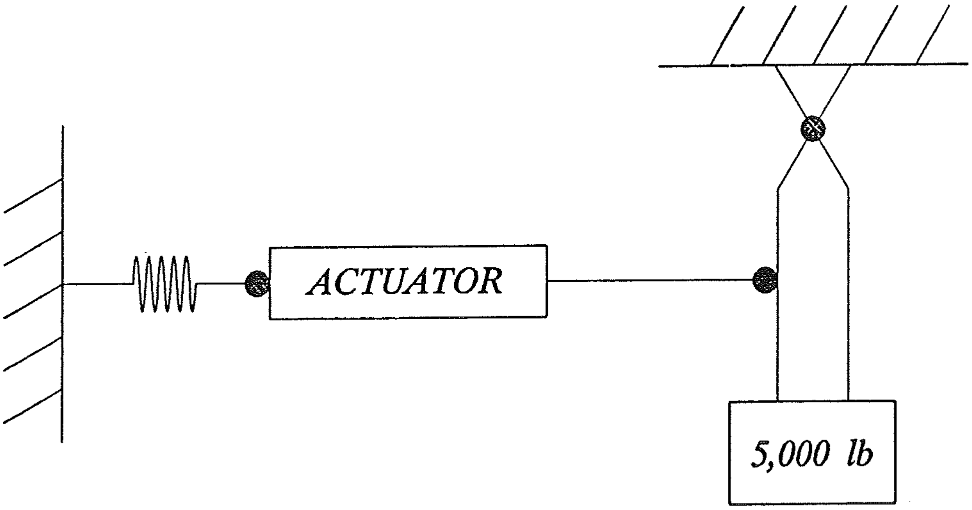
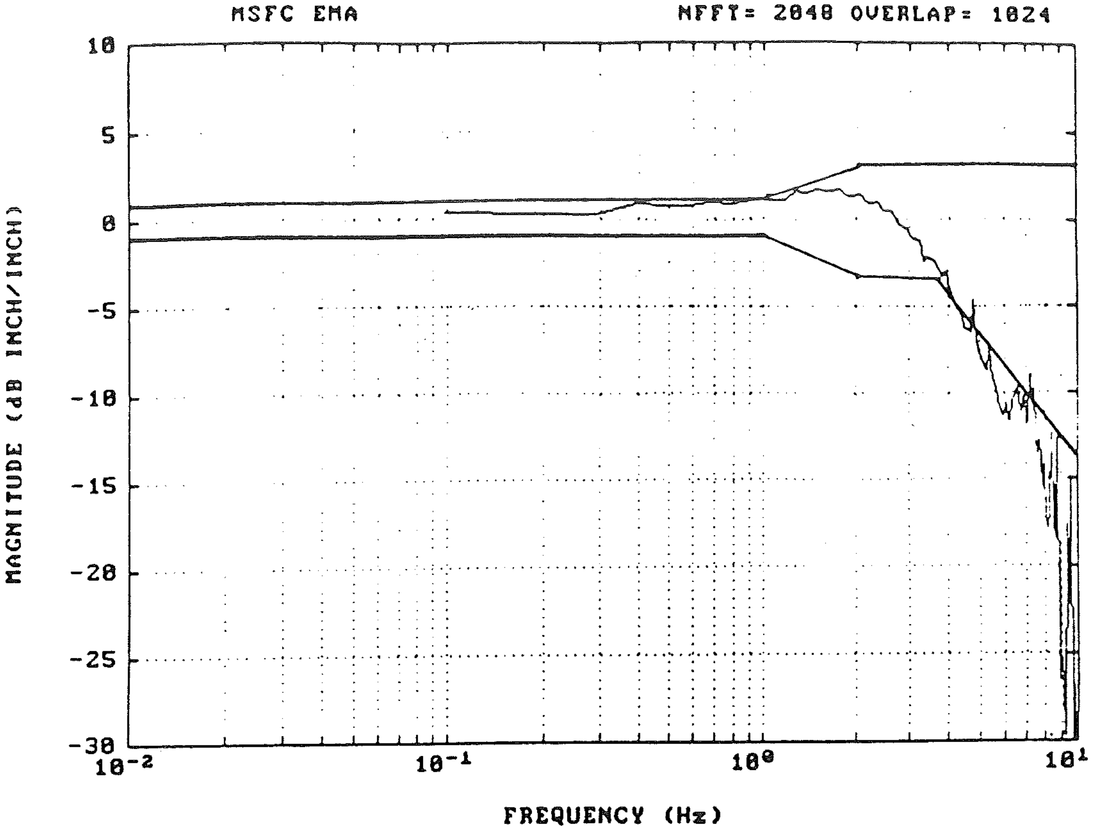


Figure 6. Dynamic Load Simulator (schematic)



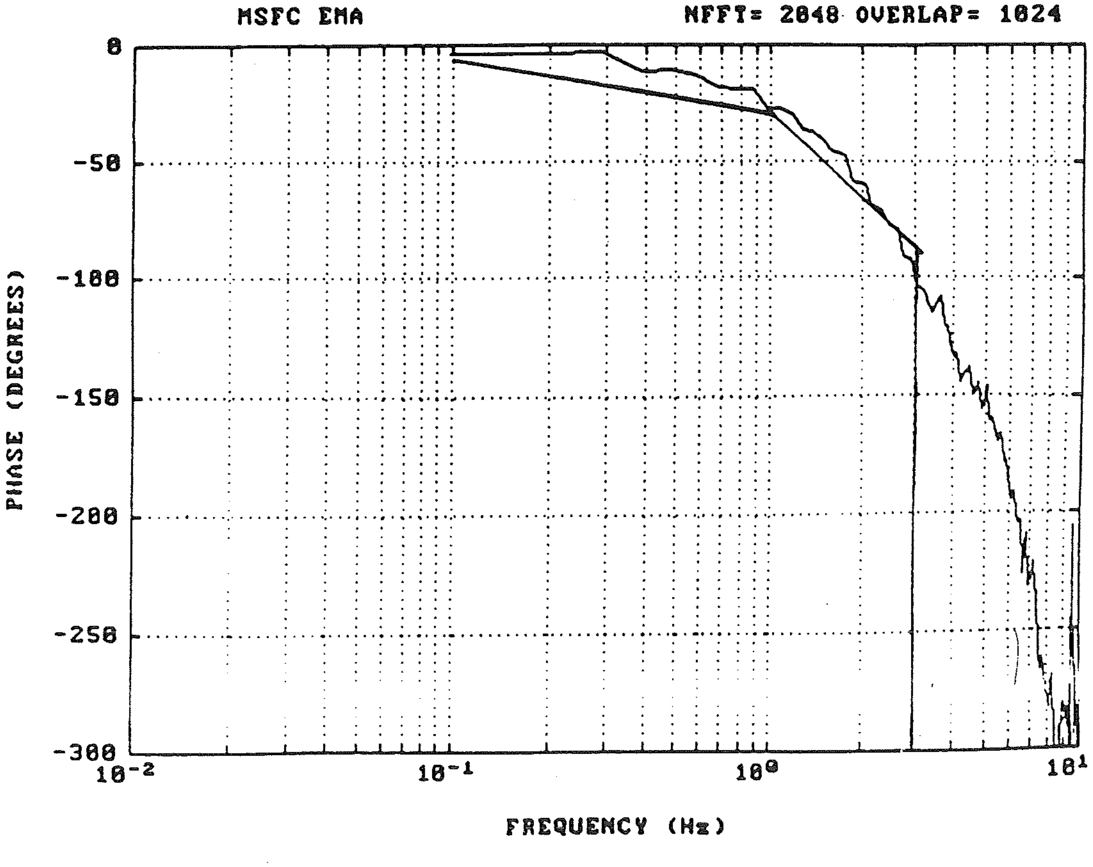
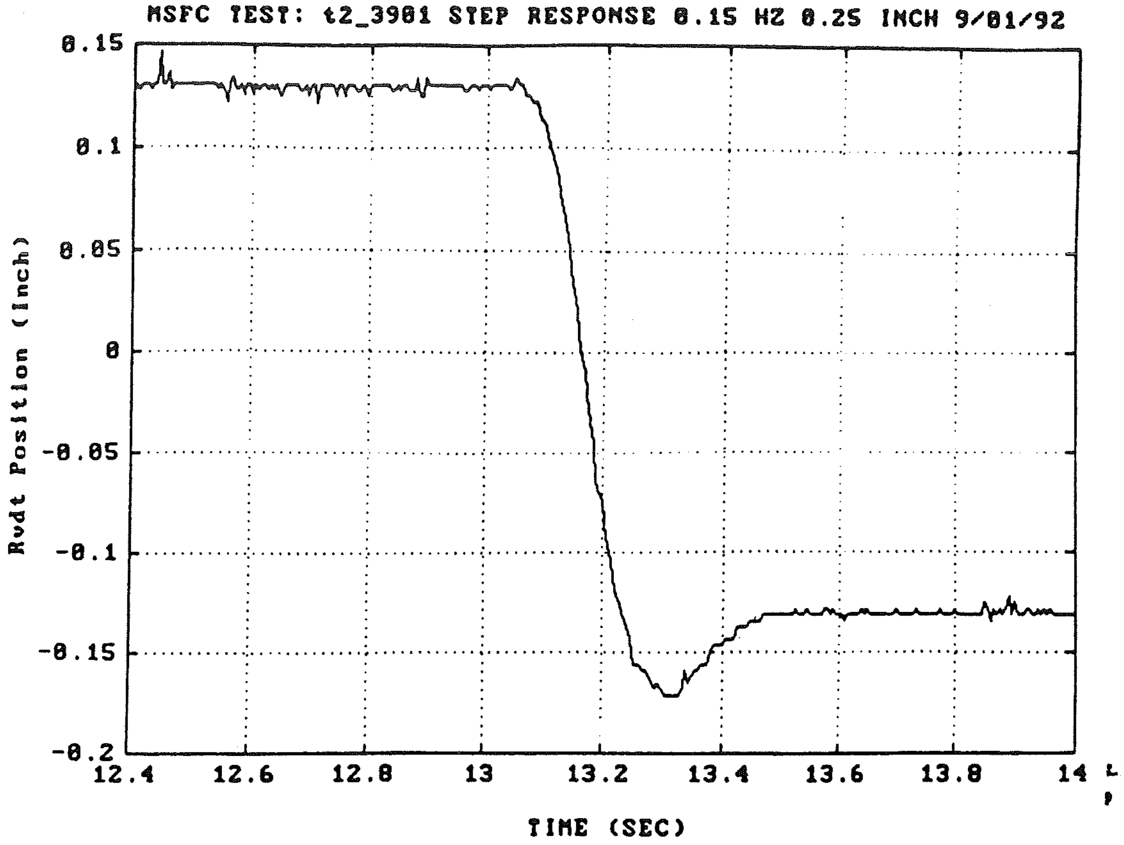


Figure 7. Frequency Response With SSME Envelope Requirements



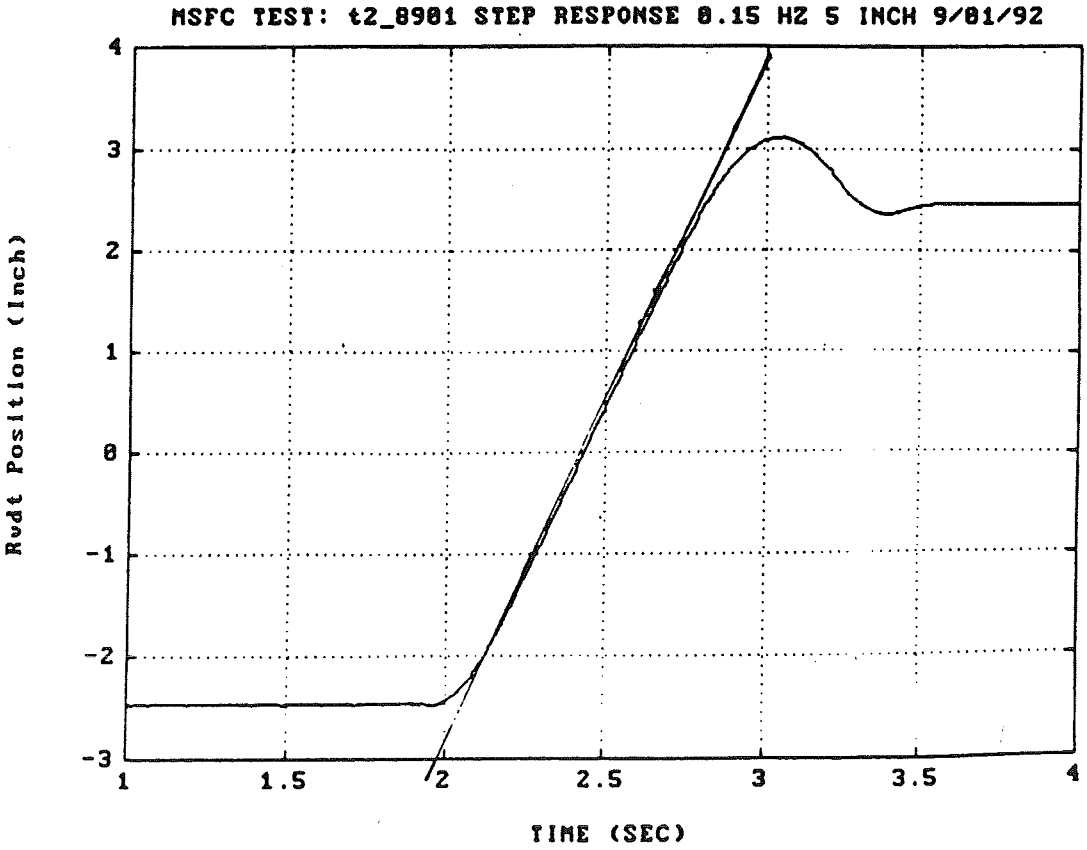


Figure 8. Small and Large Step Response

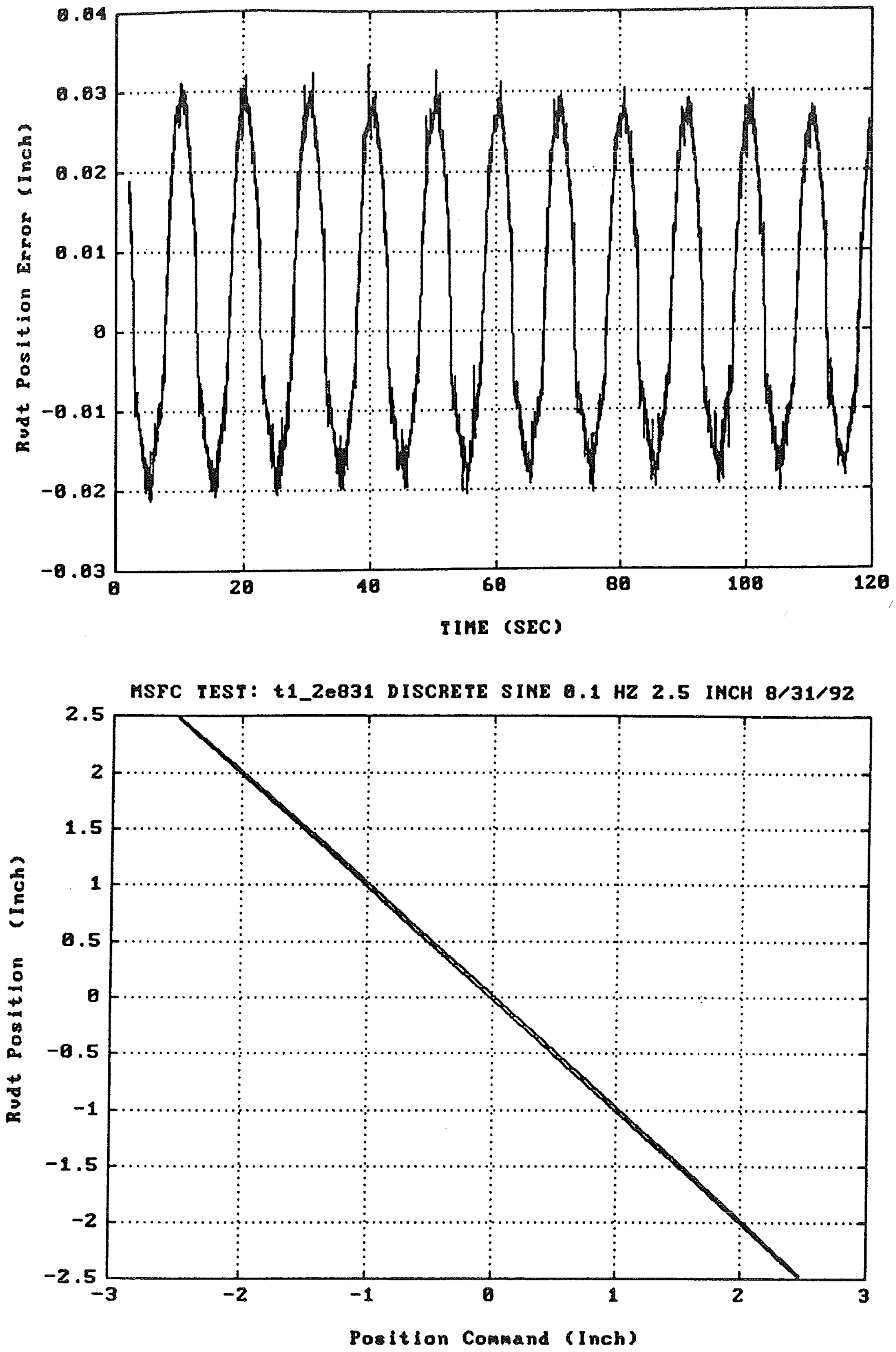
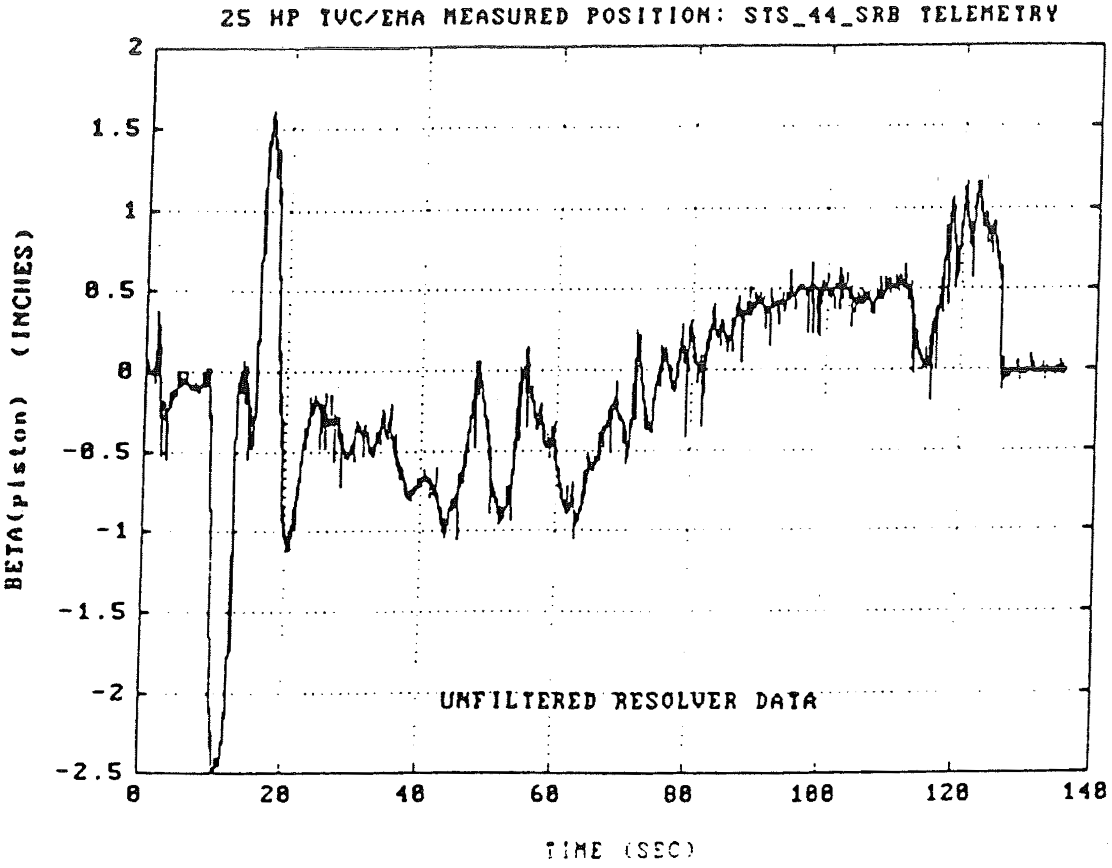


Figure 9. Large Excursion Linearity and Position Error



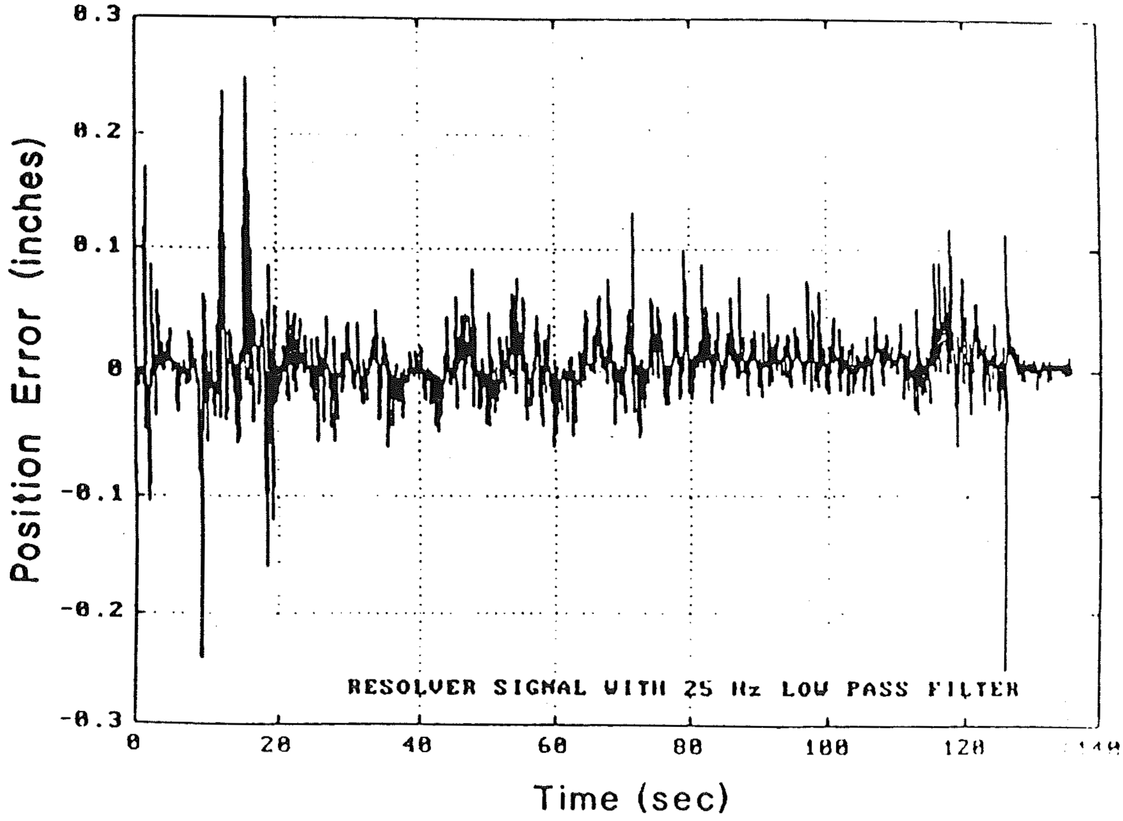


Figure 10. STS-44 Flight Profile Comparison

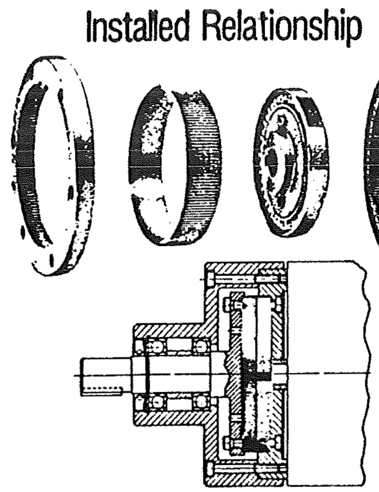


Figure 11. Harmonic Drive

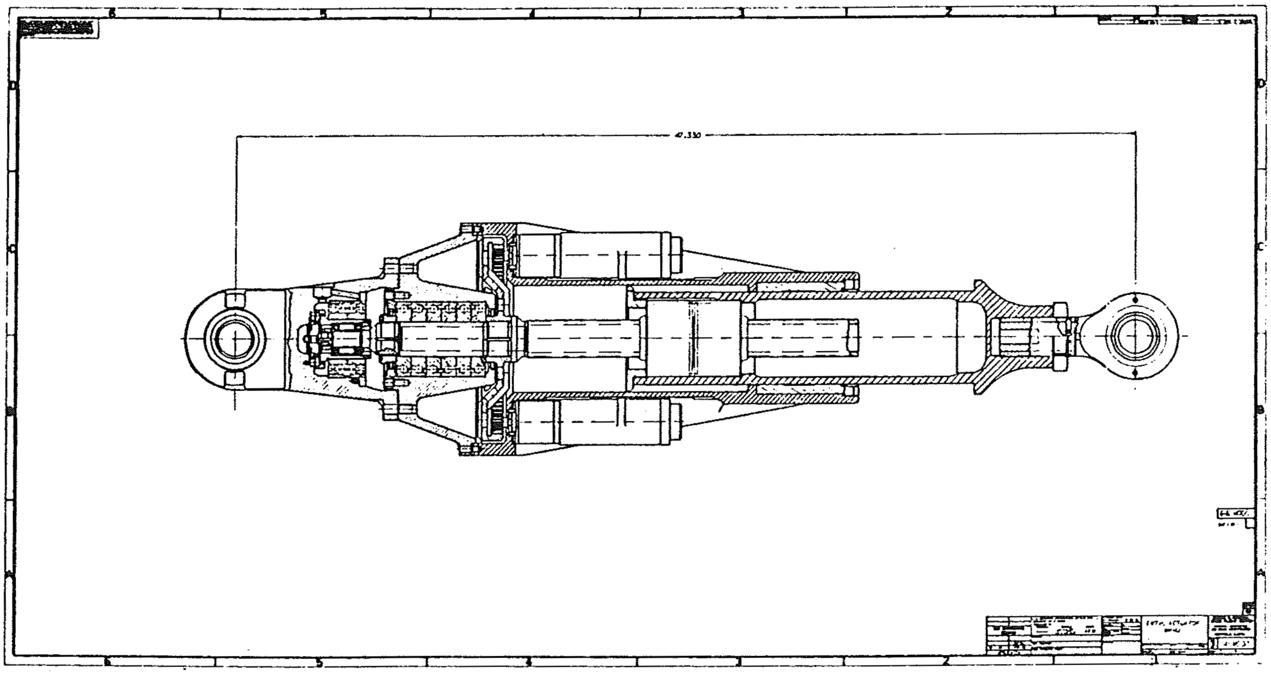


Figure 12. Second Generation EMA Assembly