Development of Mars Exploration Rover Lander Petal Actuators

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Abstract

The twin robotic missions “Spirit” and “Opportunity” were launched in the summer of 2003 as part of the MER (Mars Exploration Rover) project for a rendezvous with Mars in early 2004. These identical twin rovers were designed to prospect the surface of Mars for evidence of past geological activity related to presence of liquid water. The mission was modeled after the successful “Pathfinder” mission that delivered the “Sojourner” rover to the surface of Mars in 1997. The new rovers are much larger and heavier than the “Sojourner” and are equipped with a large array of scientific instruments as well as communication gear for direct transmission of data back to Earth. The landing vehicles have also grown in size to accommodate the new rover configuration. After the Lander makes its hard landing protected by a cocoon of air bags, it is the job of any one of the 3 Lander Petal Actuators (LPA’s) to right the spacecraft, if necessary, and open the remaining petals to allow deployment of the rover onto the surface of the red planet.

This paper describes the challenges in developing, building and testing the new LPA’s in support of the MER project.

Summary

One of the challenges to Aeroflex was to design the Lander Petal Actuator to develop 3,300 N-m of torque within the required mass budget of 6.5 kilograms. The earlier “Pathfinder” LPA’s were based on the use of a size 40, 160:1 reduction ratio, Harmonic Drive gear set as the output section of the actuator. The actuator was limited to an output torque of 1580 N-m as a result of the “Ratchet” limit of the Harmonic Drive gear set. These components were mass optimized to yield a total mass of 5.7 kg for the “Pathfinder” LPA. If a similar approach was taken for the MER actuators, the required size 65 Harmonic gear set would weigh 20.9 kg. Clearly, a new approach was required.

Each petal needs to rotate 110 degrees in 20 minutes or less giving a minimum speed requirement of 0.0153 RPM. The allowable power was a maximum of 50 watts per actuator. When the actuators were delivered to the program, the final power with brake was only 10 watts per actuator. This was accomplished through the use of planetary gear reduction systems that yield much greater efficiency at all operating temperatures (approximately 83% per stage at the cold operating temperature). The usual penalty for this approach is size for a given reduction ratio and stiffness.

Another challenge was the testing of such a large system over the required environmental temperatures (-60 to +55ºC) as well as dynamic testing of the brakes at a cold temperature of –120ºC. No off-the-shelf equipment was available for this task. A test apparatus was developed from scratch to perform the required testing while safeguarding the mission-critical hardware. This test fixture will be described later.

The MER LPA requirements were established based on the mass, size and the performance of the LPA units on the previous Pathfinder mission. These earlier units, developed by JPL, were approximately 150 mm in diameter, had a mass of 5.7 kg and were capable of a sustained output torque of 1350 N-m and a peak torque of 1580 N-m as a result of the “Ratchet” limit of the gear reduction unit employed. This mission successfully landed and deployed the Sojourner rover onto the surface of Mars in 1997. The MER mission strives to leverage the successful heritage of the Pathfinder mission to the extent possible. However, as it is usually the case when utilizing a heritage design for a new mission, some minor “tweaks” are necessary. In the case of the MER LPA’s, the minor tweak was an increase in the output

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torque from 1350 N-m to 3300 N-m. This requirement was to be accomplished without a significant attendant increase in mass or size. The high torque requirement was a result of the increase in the mass of the rover and lander package from 330 kg for the Pathfinder mission to 441 kg for the MER program. The finalized requirements for the MER LPA's were as follows:

Output Torque:	3300 N-m
Speed:	0.0153 RPM Minimum
Mass:	6.5 kg maximum
Size:	App'x. 150-mm dia. X 250-mm long
Operating Temperature:	-60 to +55ºC
Survival Temperature:	-120ºC
Power Consumption:	50 watts Maximum
Un-powered Brake Holding Torque:	> 2280 N-m

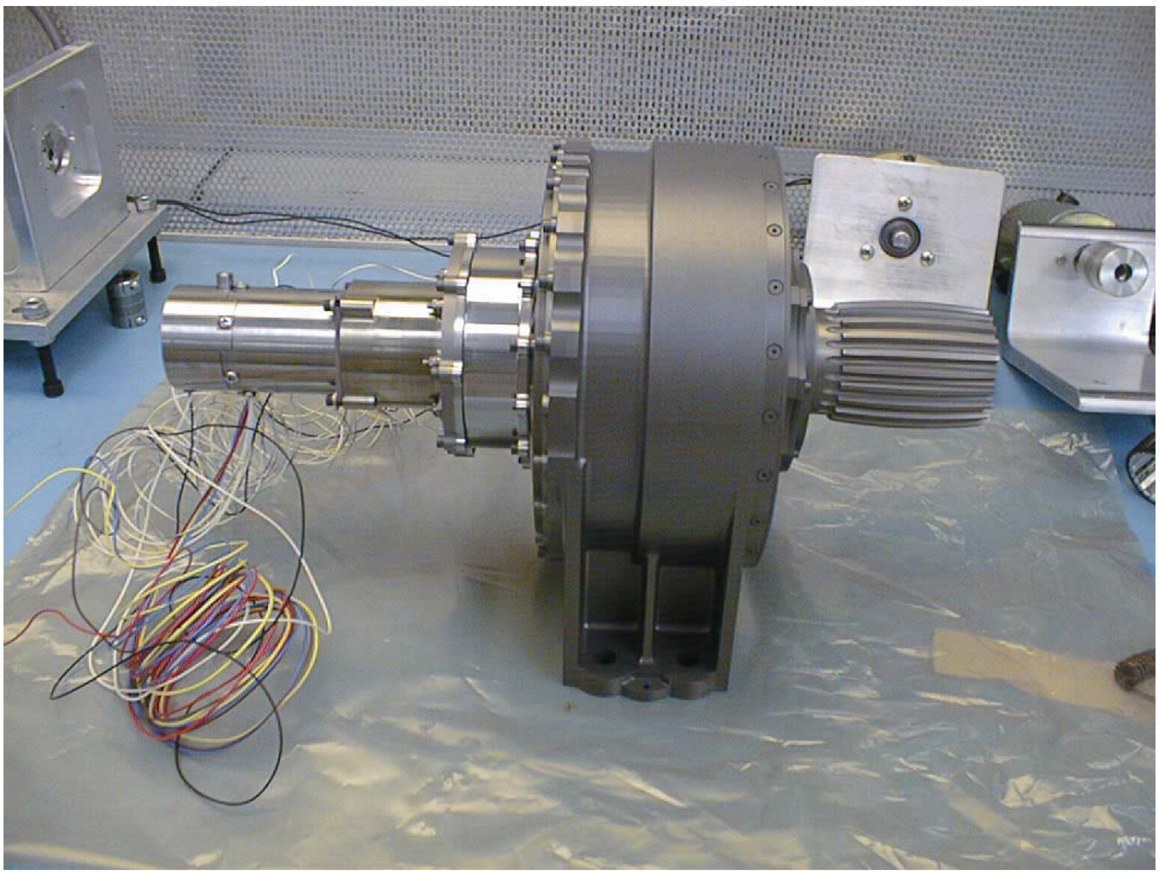

Figure 1. LPA First Article

Actuator Design

As mentioned, the use of a Harmonic Gear drive was not deemed practical due to the excessive mass penalty. Aeroflex had previously designed, tested and delivered to JPL a low mass actuator, capable of delivering approximately 2 N-m of torque at a total mass of 42 g, for use in the Muses program. Many of the design details as well as the overall philosophy of that actuator design were brought to bear on the LPA task.

This approach resulted in a design that consisted of an electronically commutated BLDC motor driving a 7-stage gear reduction system. The motor shaft was fitted with a brake to provide the required un-powered holding torque. The gear reduction was divided into 3 separate housings so that each stage may be mass optimized as much as possible. Gear geometry was selected based on transmitted torque and running speed to allow an optimum balance between the number of teeth under load, the number of planets sharing the load and the overall mass of the unit. Gear teeth were of a size 64 DP at the motor input side to an 8 DP size at the output.

The actuator has an overall reduction ratio of approximately 320000:1 and is capable of delivering well in excess of the required 3300 N-m of torque. However final torque output is limited to 3300 N-m by utilization of a current limit to safeguard the actuator as well as the hardware downstream in the torque path.

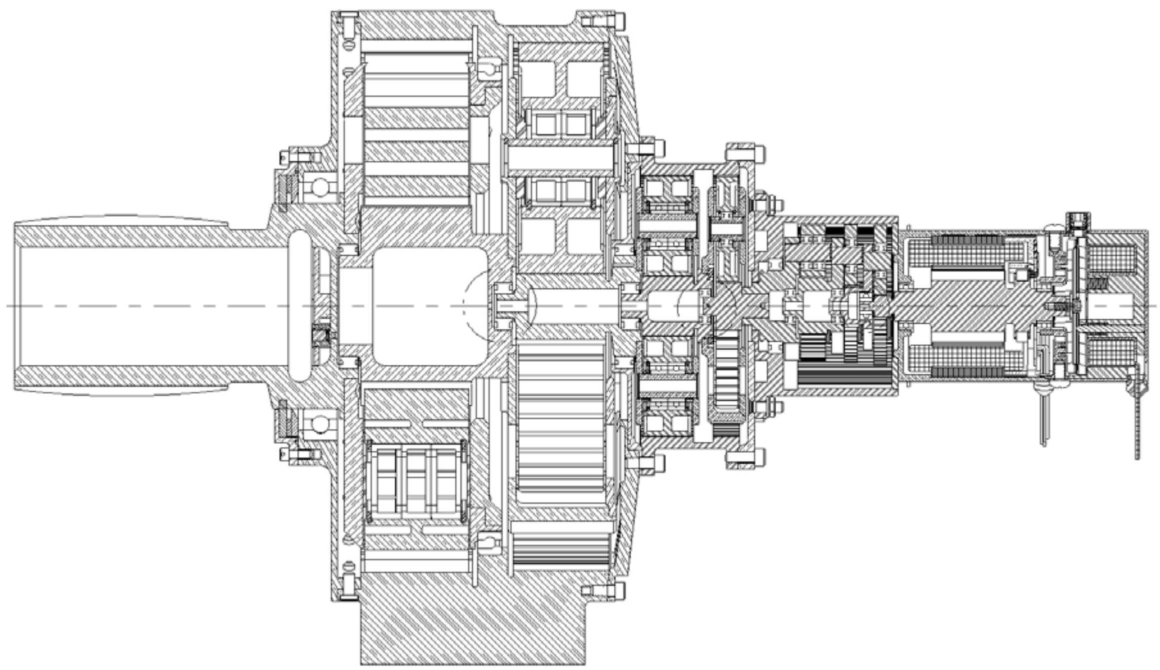

Figure 2. Actuator Sectional View

Gear Design

All of the gearing utilized in the LPA was designed and optimized using conventional CAD and FEA software. In each instance, maximum utilization of volume and mass was paramount to ensure compliance with the requirements. Each component was analyzed to allow maximum safe reduction in mass without compromising the required design margins. Particular attention was required for selection of bearings, bearing mounting and bearing pre-load selection.

As a result of the large overall reduction ratio, gear teeth at the input side were required to withstand considerably more load cycles than the output stage gearing. This would require that the input side gears be designed to have fairly moderate contact and bending stresses whereas the output section gears were primarily affected by the bending load (fatigue) stresses.

As the design progressed, it became apparent that the size of the input side gears would ultimately be governed by the available sizes of the rolling elements. The required dimensions for these bearings resulted in tooth bending loads and contact stresses that would easily meet the design loads. The effect of these size accommodations were a net increase of 70 g in the mass of the actuator.

On the other end of the actuator, a problem was encountered in fitting bearings to the output stage planets. These planets carried a load of 1450 kg at the peak output torque of 3300 N-m. The nearest size bearing(s) capable of the load were larger than the planets. The problem was resolved by selection of a roller bearing that in multiples of 3 would be able to carry the load with sufficient margin. These same roller bearings were also fitted to the second from last stage of planets with an attendant mass reduction of approximately 100 g compared to the ball bearings originally selected.

SLA Modeling as a Sanity Check

Due to the extremely tight schedule and the long lead times for fabrication of the gear components and the space rated bearings, the possibility of a pre-engineering-release prototype was out of the question. However, an SLA (Stereo Lithographic Apparatus) model was a possibility. The fabrication of the model, from extraction of the electronic files for the SLA process, until receipt of the components took approximately 2 weeks. The parts were cleaned, some minor machining was performed and a full prototype LPA was assembled using actual steel bearings and shafts. A prototype, functional motor was fitted and hence a top to bottom design verification was accomplished. This unit was actually operated on the bench. It was estimated that the plastic unit, based on the strength of the SLA materials, was capable of producing approximately 150 N-m of torque.

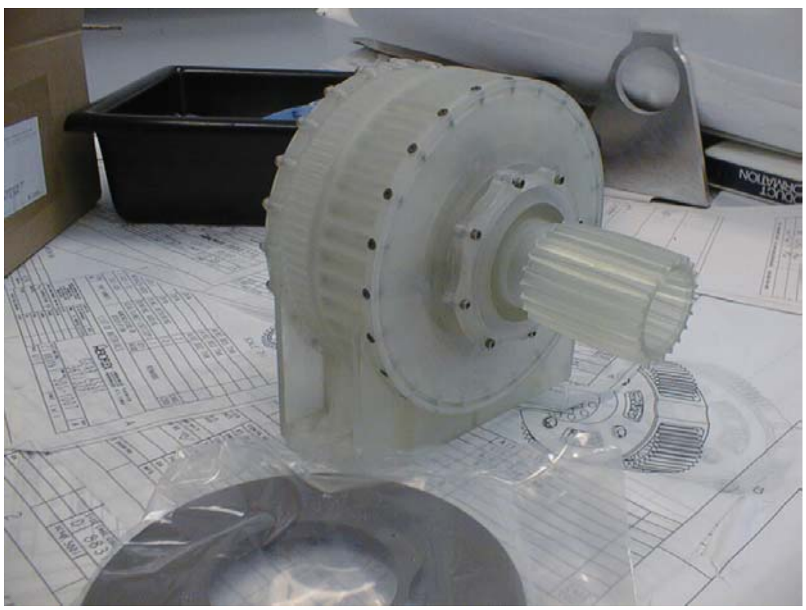

Figure 3. SLA Model of LPA

A Scary Moment

After successful integration of the actuator first article, full load testing began. Being the first time this large a load had been attempted using the relatively new Aeroflex technique, apprehension was in the air. Needless to say, design margins need to be carefully honed when the goal is as light a weight as possible.

The actuator achieved the rated torque of 3400 N-m again and again. At sometime that evening in the early morning hours, a great deal of elation was in the air and some personnel had even gone home when a loud bang was heard from the test apparatus. Of course, the couplings had snapped or perhaps even the torque transducer had failed. Fear that it was the actuator was pushed from our thinking.

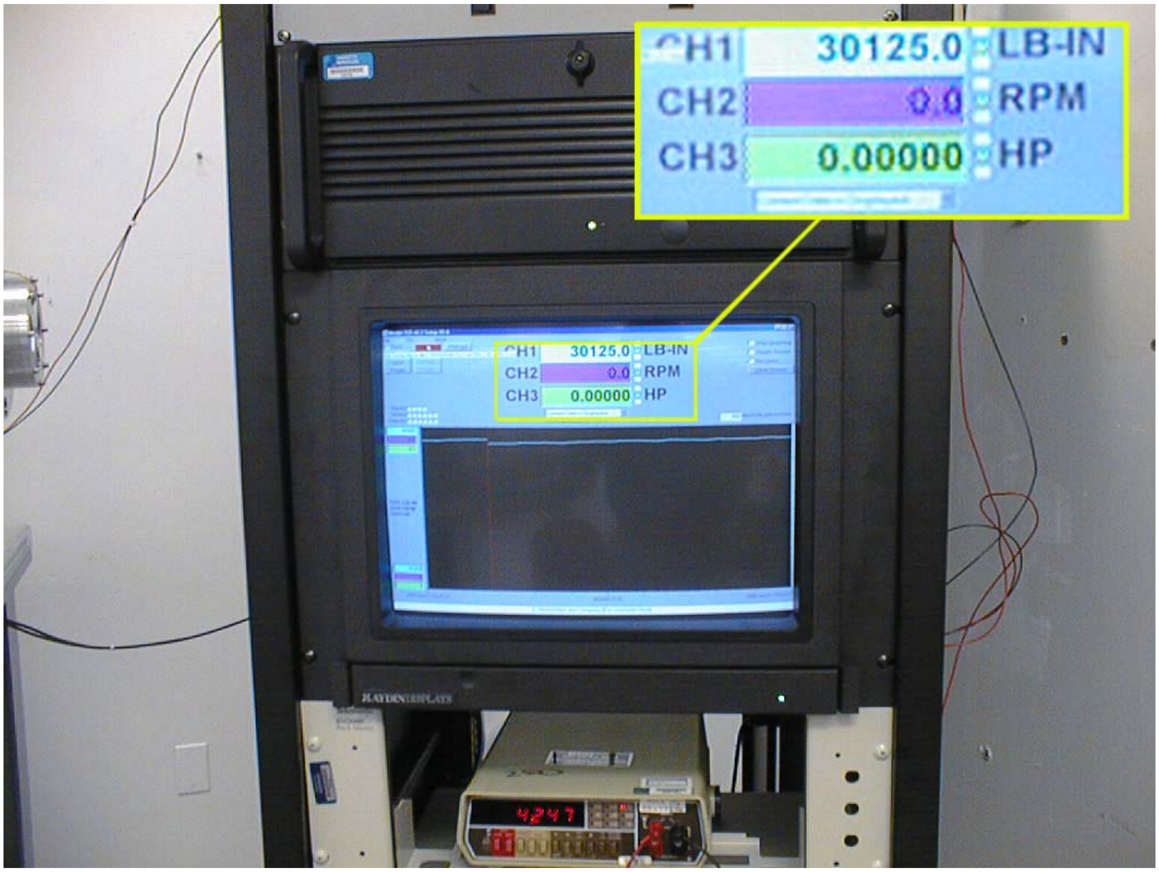

Figure 4. Moment Of Truth, Actuator Output at 3390 N-m

Indeed, after careful inspections, it was determined that a structural failure had occurred in the actuator output shaft. The output carrier to which the output pinion was affixed had snapped about the base of the pinion. Understandable since this is the region of most stress.

Further investigation revealed that the failure had occurred at a point where the wall thickness of the hollow output splined shaft was only 2.3 mm (0.090 in). The original design maintained a constant section thickness of 5 mm (0.200 in) throughout this shaft section. The section had been thinned due to the addition of a counter-bore to house the pilot bearing from the planetary stage behind the final output stage section. The size of the counter-bore was changed at the last minute when the original pilot bearing, which measured 12.7 mm (0.5 in) smaller in diameter, became untenable due to excessive lead time.

After calculations and FEA modeling had re-confirmed that the original design would have sufficient margin, the race against the clock was on to resolve the failure mode in time to deliver the flight hardware.

An additional complicating factor was that the failure had occurred in a region of the shaft immediately adjacent to an EB (Electron Beam) welded area. The condition of the welded region was carefully investigated to determine if any annealing of the material had occurred and had contributed to the failure. A careful microscopic and metallurgic examination of the failed part was performed at JPL to rule out this possibility.

Figure 5. Failed Shaft section

A Path Forward

The challenge to resolve the problem quickly and safely was compounded by the fact that virtually all the affected parts were at the end of their long (typical 16 to 20 week) fabrication cycles. There were a minimum of 5 vendors in the fabrication chain of the shaft. After a few sleepless nights, a solution was devised and proposed for implementation; rather than replace the failed part with a revised part with the intended section thickness (which would dictate the elimination of the pilot bearing or the substitution of the original unavailable bearing through the use of an off-the-shelf bearing), the part would be augmented with a series of pins inserted into the load zone to relieve the thin section of any load bearing. This solution was carefully examined by hand calculations and FEA modeling and a single part was fabricated and installed on the original EM test unit. After a few tense hours on the dynamometer, the solution was deemed a success. Additional pins were procured and installed on the remainder of the parts to support the delivery schedule. The net impact on project schedule was approximately 3 weeks.

Motor Design

The motor is a conventional 6-pole, 18-slot Brushless DC design with a center tap which is driven unipolarly. The drive electronics (LPAE's) were developed and manufactured by JPL. Because the actuator is capable of torques greater than 3300 N-m, current limiting in the LPAE controllers was necessary to prevent damage to downline mechanisms and was set using the first actuator.

The motors have a Kt of approximately 35 mN-m/amp with a winding resistance of approximately 5 ohms. The motors were capable of delivering approximately 12 mN-m (1.75 in-oz) of torque at the current limit. Motor speed varied from approximately 5000 to 7000 RPM depending upon supply voltage.

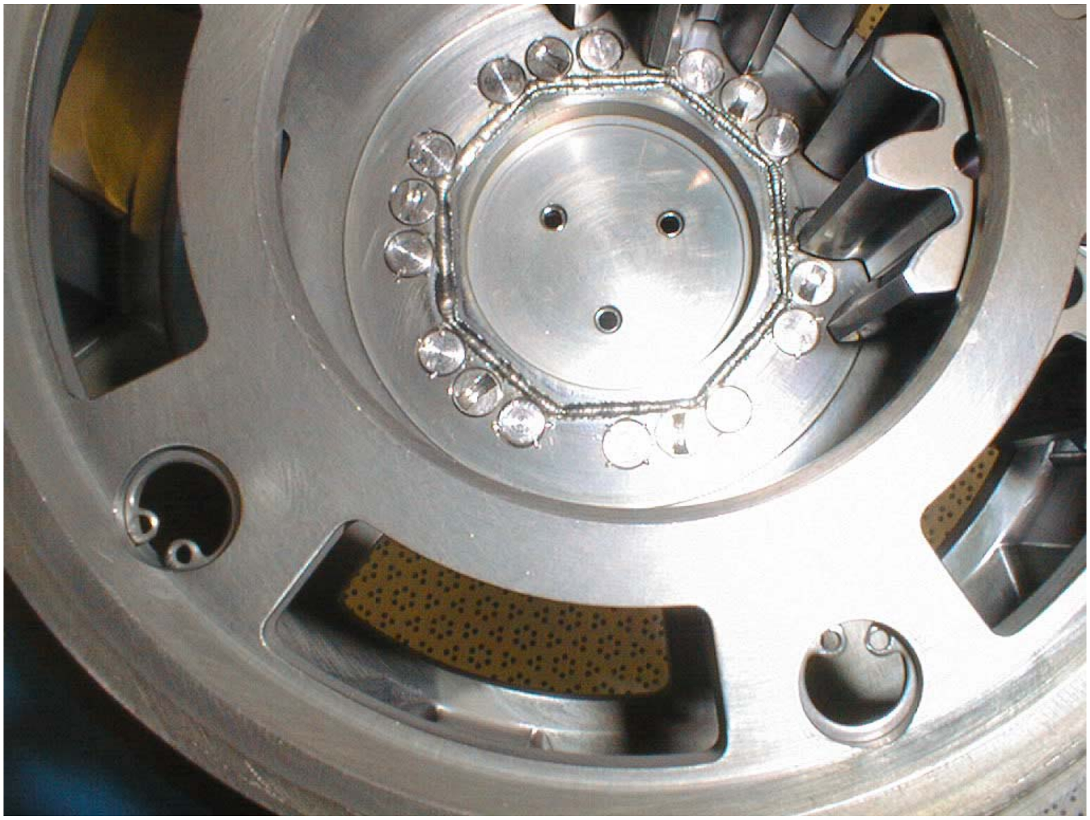

Figure 6. Pinned Shaft section

The motors were commutated using 3 latching ceramic Hall devices placed with a 120-degree electrical separation. Because the Hall devices contain electronic components, extreme caution concerning ESD and voltage excitation conditions had to be observed at all times. When not connected to the drive electronics, all commutation leads were twisted together. The motor used a separate magnetic target to excite the Hall devices. This allowed a 180-degree sensor pole arc target to be used to ensure CW and CCW performance was symmetric to within a small percentage of one another.

Each motor/brake assembly required passing a separate test procedure before integration with the gear assembly.

Brake Design

The brake is a conventional electromagnetic type used in other space mechanism motors developed by Aeroflex. The brake has 6 springs which forces two discs together. The discs have lapped chromium oxide surfaces which produces the friction. One disc is fixed to and rotates with the motor's rotor. The other disc is allowed to move axially and is rotationally restrained with 3 polished pins. The engaging motion is too short and the pin clearance too large to allow the pins to cock and hang up. To disengage the brake, an electromagnet is energized and attracts the disc that is restrained from rotation by the 3 pins. This action separates the two discs allowing the disc affixed to the rotor to rotate freely.

Only a few watts of power is necessary to release the brake. A non- magnetic spacer was inserted between the electromagnet and the movable brake disc to prevent residual magnetism from holding the brake dis-engaged once power is removed. The brake friction torque also exceeds the motor's capability of rotating the system (approximately 35 mN-m), i.e. if the motor was energized with the brake engaged, the motor would not turn.

There was a condition where a brake did not release in one of the 12 units manufactured. This interesting development and the resolution of the condition are described in detail in another paper presented by JPL.

Test Apparatus

Due to the extremely high torques produced by the LPA, it was necessary to design a special test bench. This test bench holds the LPA within an environmental test chamber while allowing torque transmission to the torque transducer and torque generating elements mounted in-line with one another outside the chamber. The LPA unit under test (UUT) was mounted on a custom fabricated cold plate held on the end of four 5-cm (2.0-in) diameter rods which passed through the walls of a modified thermal chamber and were anchored to a 4.4-cm (1.75-in) thick aluminum plate which comprised the base plate of the test fixture. This configuration isolated the chamber from all of reaction forces and allowed the torsional loads of operating the LPA to be resisted by the robust construction of the test bench.

The goal of the testing program was to measure the torque and speed of the LPA at different applied voltages (24 to 32.8 volts) as well as different applied torques (0, 680, 1355, 2033, 2260 Nm) up to 3300 Nm under various thermal conditions (-60 to + 60ºC). Some special brake testing was to be performed at –120ºC.

Because the LPA moves at such a slow rate of about 0.018 RPM (on average), conventional brakes would not work. Problems such as "stiction" for example could cause erratic torques leading to test anomalies. In the final configuration, in order to maintain smooth, precise control over the resisting torque, the LPA was allowed to drive a large step up gear system with an overall ratio of 1:17400 with a Himmelstein torque transducer mounted between the LPA and the load. The input to this gear system was a small control motor. With the small control motor stalled, the LPA could wind up the system to the maximum torque required. Running the small control motor in the same direction as the LPA would allow any torque loading required. Running the control motor to match the speed of the LPA would produce a no load condition to the LPA.

During testing a number of parameters, such as torque, velocity, motor voltage, brake voltage as well as a number of thermo-couples placed at various points on the LPA and the test chamber were continuously logged and recorded. The actuator was required to rotate 1 complete revolution in both CW and CCW directions under each of the specified environmental conditions at various voltages and loads. As an example, at a load of 2260 N-m with a 32.8 volt supply, the LPA required 55 minutes to complete a revolution in one direction.

To achieve the –120ºC temperature in a "standard" chamber which is only capable of a –75ºC lower temperature, a controlled flow of Liquid Nitrogen (LN_2) was introduced into a cold plate incorporated into the mounting base for the LPA. This was augmented, under closed loop control, by direct injection of LN_2 into the chamber itself. This method is not recommended by the chamber manufacturer as it freezes the refrigerant and trips limit relays. It takes several hours for the chamber to recover and operate normally.

The low temperature testing was to ensure that the brake would hold during the Mars night and not allow the petal to slip and upset the rover. The test actually included electrically releasing the brake with a torque applied to the LPA output shaft simulating the rover load and then re-engaging the brake when electrically deactivated.

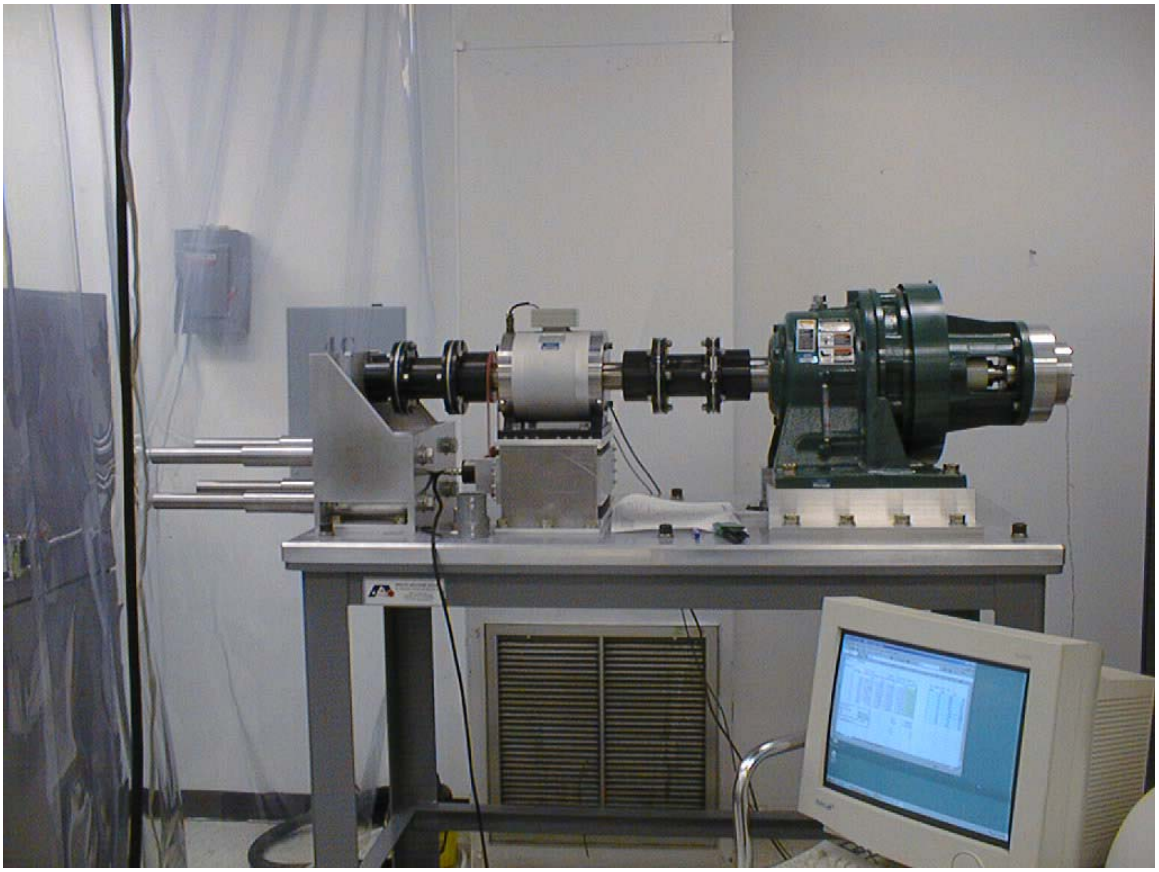

Figure 7. Dynamometer Portion of Test Apparatus

A total of 12 LPA's were assembled, tested and delivered to the MER project.

The results of the testing were a validation of the many design assumptions employed in the construction of the LPA's. In particular, the performance of the actuators over the required temperature range without the use of heaters or blankets was indicative of excellent gear efficiency and lubrication performance.

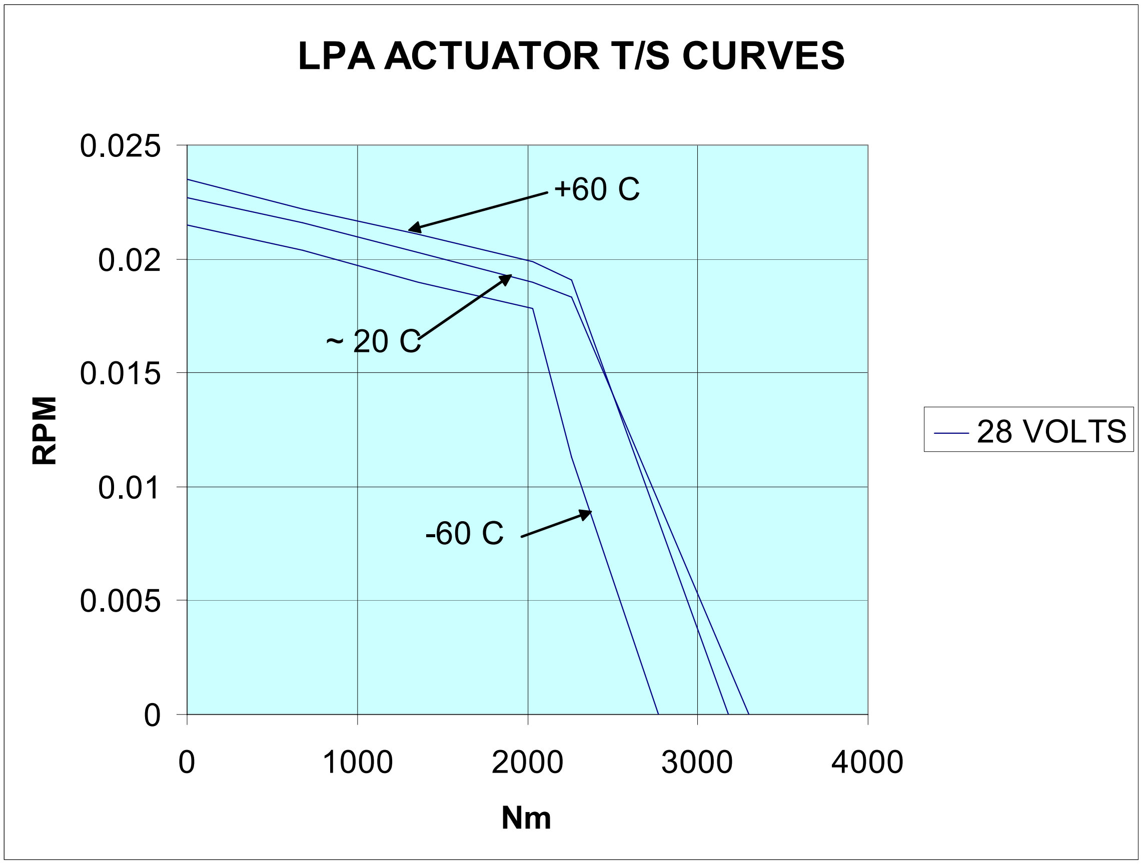

Figure 8. Actuator Torque/Speed Curve vs. Temperature

Lessons Learned

The LPA's were designed, built, tested and delivered under an extremely tight schedule. The key to the success of the project was extensive and early testing. SLA modeling was a great resource in determining design viability at an early stage.

An early and comprehensive overview of the design may help illustrate the relevant long poles of the effort at an earlier stage.

The use of planetary gear reduction for high torque applications is a viable approach so long as stiffness requirements can be satisfied with the values attainable with these systems. Careful selection of materials, gear size and lubrication is necessary to balance surface pitting (contact stresses), gear fatigue life (bending stresses) requirements vs. size and stiffness.