Mass Properties Testing of the Mars Exploration Rover Missions*

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ABSTRACT

Lockheed Martin Space Systems Company (LMSSC) Denver, under contract to the Jet Propulsion Laboratory (JPL) performed the mass properties testing of the Mars Exploration Rover (MER) missions. This testing occurred over a ten-month period at both the Jet Propulsion Laboratory and Kennedy Space Center (KSC). The tests at JPL were performed to verify model accuracy and determine any issues that may affect the final mass properties measurements at the KSC launch site. Testing at KSC was performed on the Entry Vehicles and the fully fueled spacecraft configurations for both the Spirit and Opportunity missions. All tests were completed successfully contributing to both mission's successful launch and subsequent landing on the surface of Mars in January of 2003.

INTRODUCTION

Due to the complexity of the two spacecraft and the various configurations of flight each went through, several subsystem mass properties measurement tests had to be performed prior to the final launch configuration spins. A Research Support Instruments (RSI) 3000 lb. capacity Spin Table was used to acquire center of gravity (cg), moment of inertia (MOI) and product of inertia (POI) measurements about the principle axis for each of the spacecraft configurations. Five separate tests were performed at JPL followed by four separate spins of the fueled spacecrafts at KSC as shown in figure 1. This paper describes the testing sequences used for model correlation and final mass properties verification of the MER spacecrafts as well as describing some of the unique capabilities of the LMSSC Spin Table.

Figure 1- Spin Table/MER Spacecraft

* The testing described in this paper was performed under Lockheed Martin contract #1222626

SPIN TABLE DESCRIPTION

The Reverberant Acoustic Laboratory at Lockheed Martin Space Systems Company (LMSSC), Denver has developed the capability to perform large-scale system level mass properties testing by transporting a Spin Table to the site at which it is needed. The majority of Spin Tables used to perform mass properties testing are not mobile and are permanently setup in one location. Conventional thought is that these instruments should not be moved due to the high risk of damage to sensitive components. LMSSC has developed a method for transporting the equipment to the desired test location. By transporting the Spin Table to the spacecraft's integration and testing facility, risk to the test article is greatly reduced. Transporting the table itself is also more cost effective that transporting the test article offsite. Performing the testing this way reduces the schedule time needed to perform the mass properties measurements. The test article does not have to be moved therefore normal integration can be performed with stoppages only while the testing is in progress. For this testing, the Spin Table was packaged and shipped to JPL and KSC. Once the table is in the desired location, it takes approximately two weeks to fully setup and check out the equipment.

The LMSSC Spin Table shown in figure 2 is fully vacuum compatible as well as Class I, Division 2 rated for Isopropyl alcohol (IPA) or other referee fluids to simulate fuel loads while spinning in air or vacuum. A spacecraft loaded with Hydrazine or other propellants can be spin tested at KSC.

For large asymmetrical spacecraft where lift or drag is a concern with air measurements, LMSSC has a 14-foot diameter Bell Jar capable of spinning large spacecraft in vacuum. The Bell Jar can be pumped down to 5 torr. This allows for model correlation between air and vacuum for later use on the fully loaded spacecraft at KSC where there is not vacuum capability.

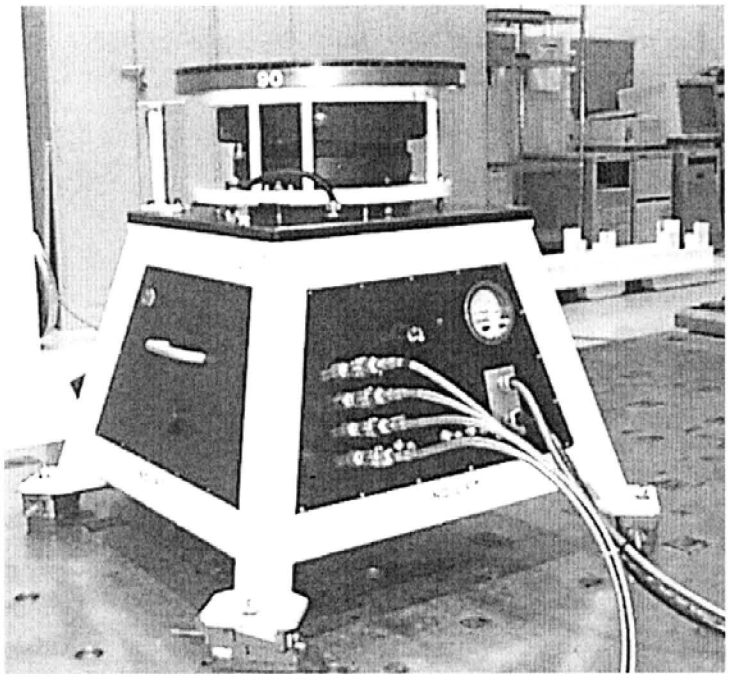

Figure 2- LMSSC Spin Table

The MARK 10-3000 Mass Properties Measurement System (MPMS) is a mass properties testing device capable of measuring center of gravity, moment of inertia, product of inertia (Ixz and Iyz) and dynamic balance of test objects up to 3000 pounds. Center of gravity measurements are determined by measuring moments to accuracy within ± 0.33 in-lb. of radial offset. Moment of Inertia measurements are determined by using an inverted torsion pendulum to accuracy within ± 0.1%. Only aerodynamic effects limit this

measurement. Product of Inertia measurements can be measured to an accuracy of ± 0.90 lb.-in^2 at 50 RPM. POI is measured about the bearing center 3.75 inches below the tabletop and converted to POI about the center of gravity. The speed range of the table is 20 to 220 rpm.

The RSI Spin Table is a single load cell unit. Center of Gravity measurements are performed at speeds between 3 to 5 RPM in the clockwise and counter clockwise directions. The two values are then averaged to obtain the final cg measurement. The method of locating the center of gravity involves measuring the offset force (moment) created by the test article on the machine. The test article is supported while spinning by a spherical air bearing. If the effective centroid of the test object does not lie precisely on a vertical line projecting upward from the center of the support sphere (Z axis) a moment is created. The moment is resisted by an equal and opposite moment applied to an additional spherical bearing at the bottom of the table. A stabilizing shaft connects the two bearings.

When the centroid of the test object is displaced a given distance from the vertical measuring axis of the machine, it lies in a certain angular relationship with respect to an arbitrary or geometrical axis of the test item. The centroid may also be thought of as a vertical plane that contains the vertical machine axis and the centroid. As the spherical bearing and test items are rotated, this plane rotates about the vertical axis of the machine.

The moment produced by the center of gravity offset is balanced by a moment applied to the spherical bearing. The stabilizing bearing at the lower end of the shaft supplies this balancing force. As the test object is rotated the force on the stabilizing bearing also rotates. The stabilizing bearing is supported in a flexure and gimbal arrangement so that there is one direction of unrestrained movement. A load cell provides the restraint in this direction. The transducer is responsive only to the force or component of force directed along this single axis.

Measurements are made continuously as the test object rotates. This data is summed to produce a precise measurement of the force component. The force components provide the resultant force (moment) and the angle. Once the resultant moment force has been determined, the actual center-of-gravity offset with respect to the Z-axis can be obtained by dividing the moment by weight of the test article.

Product of inertia can be determined by measuring dynamic unbalance at different speeds. Dynamic measurements are made by spinning in both the clockwise and counter-clockwise directions. Spinning in two directions and averaging the results reduces the influence of aerodynamic drag. Product of Inertia is calculated using moment data captured by the load cell

A two-speed method is the preferred method for performing POI measurements. Large test articles are typically spun at 20 and 40 rpm in the clockwise and counter clockwise directions. The greater the separation between the two measurement speeds, as well as the higher the rotation speed, the more accurate the measurement will be. Spin Table accuracies for cg, POI and MOI measurements are listed in Table 1.

The Spin Table is equipped with an inverted torsion rod which is used to perform MOI measurements. This measurement is obtained by clamping the lower end of the torsion rod in the torsion rod chuck. With the torsion rod clamped, the test item and spherical support bearing are no longer free to rotate. They are angularly displaced through a small angle against the elastic restraint of the torsion rod. When the torsion rod chuck released, the assembly oscillates about the spin axis. The oscillation is essentially frictionless and undamped with the exception of air drag due to the near frictionless environment in the gas-supported bearing. A photo eye mounted in the table measures the period of oscillation. The technique is to perform all measurements at a specified amplitude. After the average period of oscillations is measured, the gross amount of inertia of the rotating system can be calculated by subtracting the tare moment of inertia of the table and fixturing from the measured gross moment of inertia of the system.

Table 1- Spin Table Accuracies

C.G.	+/- 0.33 lb-in
POI	+/- 0.90 lb-in^2
MOI	+/- 0.1%

MER TESTING AT JPL

The two Mars Exploration Rovers launched on June 10 and July 7, 2003. The primary goal of Spirit and Opportunity missions are to search for signs of water by examining a wide range of rocks and soils. The Spirit rover successfully landed at the Gusev Crater on January 3, 2004 followed by the Opportunity Rover's landing January 24, 2004 on the Meridiani Planum. The missions were originally scheduled for 90 days but have far outreached those expectations and are still functioning today. Figure 3 illustrates the various components of the MER spacecraft.

One of the challenges of these tests was that the MER missions have several configurations that had to be tested separately, correlated and then tested as a whole system. Each spacecraft consists of an Aero Shell, Cruise Stage and rover. During flight, the Cruise Stage provides propulsion and navigation for the spacecraft as it approached Mars. Upon arrival, the Cruise Stage is jettisoned and the Entry Vehicle consisting of the Aero Shell and rover descends to the surface. At the appropriate time, pyros fire and the Aero Shell breaks away from the rover. At this point a parachute deploys and the rover coasts towards the surface. A complex system of airbags encases the rover and bounces on the surface until coming to a stop. From here the rover is deployed and free to roam the surface of Mars.

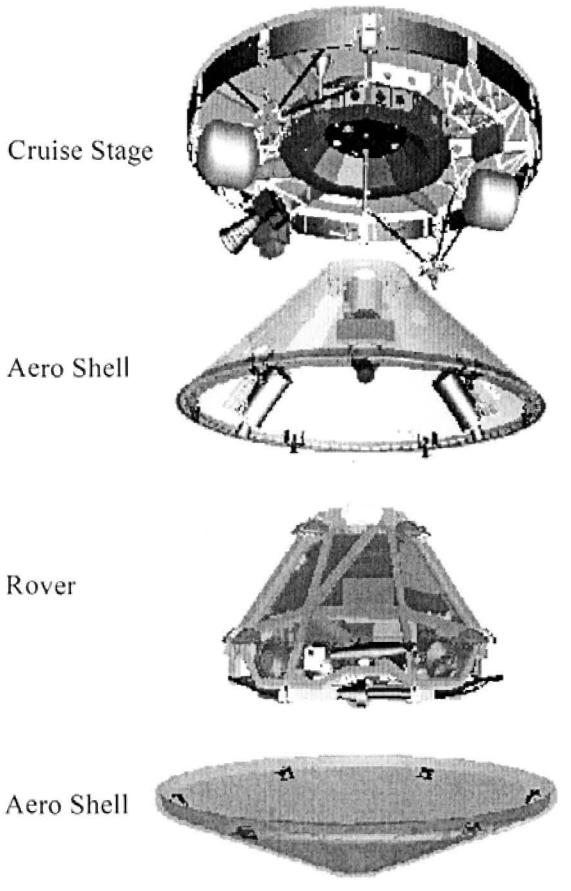

Figure 3- MER Spacecraft Exploded View[1]

[1] Figure 3 was supplied by JPL

The testing sequence began at JPL in early September 2002. The main goal of this testing was to verify the mass properties models. The first test article was an empty Aero Shell. A typical test sequence begins by taking a MOI measurement. This is necessary because the test software uses a known MOI in its calculations to determine the motor output needed for a POI measurement. The next step is to take a low rpm cg measurement. Along with obtaining the test article's center of gravity, it also helps the operator determine if the vehicle moments will overload the Spin Table during a high rpm POI measurement. If the maximum moment levels are too high during the cg run, ballast will have to be added before the POI measurement is taken.

It was necessary to test the MER spacecrafts in several sections due to the different flight configurations during cruise and landing. This test gave the program Mass Properties Engineer (MPE) a feel for how the Spin Table functioned as well as insight into how it reported the final data. There was good correlation between the models and the actual test data. Once the MPE and the Test Conductor (TC) determined that the data was adequate, the ballasting sequence was able to begin. Another main goal of these preliminary runs was to verify the modeling tools use to determine the ballast weights needed. After the initial Aero Shell measurements were taken, the MPE determined the ballast weights needed to bring the Aero Shell within specifications for CG and POI. The testing at JPL was not intended to be used for final balancing. Once all desired data was collected, the ballast weights were removed so that further vehicle integration could resume. Testing then began on a second test article.

The second test article tested was one of the two spacecraft Cruise Stages. This article was tested to correlate test models as well as determine the feasibility of using the Cruise Stage as a ballasting surface when balancing the full spacecraft. The Cruise Stage was symmetric and low in profile but had instrument boxes and propulsion modules that created significant drag during the test. The drag was so high that the Spin Table motor was unable to overcome it. The POI spin speeds had to be lowered from 20 and 40 rpm to 20 and 30 rpm. This is not the desirable separation between the two speeds but was still acceptable.

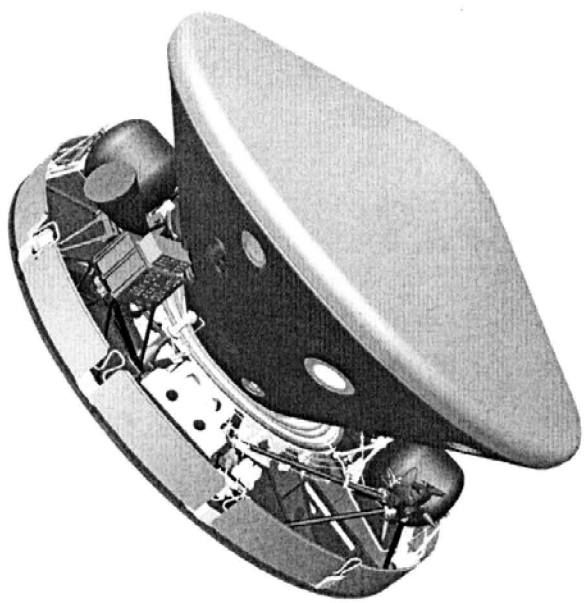

Figure 4- MER Spacecraft[2]

The final sequence of testing involved both Entry Vehicles and one full spacecraft shown in Figure 4. All three test articles showed good model correlation. One concern at the beginning of testing was that there would not be adequate mounting points to hold ballast weights if large amounts needed. Through several balancing runs, it became evident that there were several good points to mount ballast weights.

[2] Figure 4 was supplied by JPL

The testing at JPL was a success. Once all of the data had been reviewed, the MPE was able to determine what needed to be done to the test models prior to final testing at KSC. The Spin Table was deconfigured and packed for the trip to the launch site. Table 2 summarizes the location and tests performed.

Table 2- Spin Test Matrix

TEST LOCATION	TEST ARTICLE
JPL	MER 2 Aero Shell
JPL	MER 2 Cruise Stage
JPL	MER 1 Spacecraft (Dry)
JPL	MER 1 Entry Vehicle
JPL	MER 1 Cruise Stage
KSC	MER 2 Entry Vehicle
KSC	MER 1 Entry Vehicle
KSC	MER 2 Spacecraft (Wet)
KSC	MER 1 Spacecraft (Wet)

KSC TESTING

One significant capability of the LMSSC Spin Table is that it meets the requirements of Class I, Division 2 and as such is able to perform testing on fully fueled spacecraft. As the MER crew began final integration of both spacecraft, LMSSC personnel unpacked, setup and operationally verified the Spin Table system. A challenge that spinning a fueled spacecraft poses is that no personnel can be inside the facility during testing due to the potentially hazardous environment if there is a fuel leak. The table must be operated remotely from outside the facility. To accommodate this, the spacecraft integration facility was supplied with a trailer that the Spin Table operating equipment could be setup in and the necessary cables and hoses were fed into a pass-through in the wall. Since the Spin Table was operated remotely, the test was monitored using video cameras.

Prior to testing, a significant software modification was completed. The air drag from the Cruise Stage of the spacecraft made it difficult to hit the precise tolerance at which the software would begin to take data once the required rpm had been reached for a POI measurement. While testing at JPL, the table was unable to reach these tolerances. As the Spin Table approached the desired rpm, it would overshoot the value. The software would sense the high rpm and try to slow the table motor down. This along with the significant air drag from the Cruise Stage would bring the spin speed down too far. This cycle occurred until the table began to overheat and the test had to be aborted. The software modification opened the tolerances and allowed greater control, significantly reducing the chance of the table missing the desired rpm for acquisition of a POI measurement. This decreased the time each test sequence took and saved the MERprogram a large amount of schedule time. A typical cg, MOI and POI test sequence would take up to five hours before the modification. After the software was changed, a test sequence took around two hours.

The final test series involved the final balancing of both flight Entry Vehicles along with each fully fueled spacecraft. Each test sequence of an individual test article took approximately two days. This included all necessary measurements and the addition of ballast weights. All phases of testing went as planned and each article was balanced to within program specifications. Figure 3 summarized the final cg and wobble angles for the Spirit and Opportunity spacecrafts.

.After all the test objectives were met, a post test verification was performed on the bare Spin Table to verify that no major perturbations to the setup had occurred since it was originally setup in the facility. This involves measuring the cg of a known 50-pound weight and comparing that value to the same measurement taken prior to test. From arrival and checkout to the end of testing, the Spin Table was setup for four months. Once the test team was able to break configuration, the equipment was packed and shipped back to LMSSC in Denver.

Table 3- Final Balance Data[3]

Spacecraft	Xcm (mm)	Ycm (mm)	Zcm (mm)	Wobble Angle (deg)
MER 2	0.3	0.4	663.5	0.13^{0}
MER 1	-0.32	0.24	664.8	0.04^{0}

CONCLUSION

The unique capability LMSSC, Denver has developed to transport a Spin Table to the site at which it is needed, gives programs the ability to test fully loaded at the launch site as well as obtain preliminary measurements at a site where it would not be possible. This saves the schedule time and cost of shipping the entire test article offsite enabling the spacecraft team to stay in familiar surroundings to integrate until just prior to testing. Since there is not an adequate way to spin balance fueled spacecraft at KSC, this ability also gives programs the chance to verify the mass properties characteristics of a spacecraft in its flight configuration.

The mass properties testing of the Mars Exploration Rovers was a great success. All test articles were balanced to within specifications contributing to both mission's successful launch and subsequent landing on the surface of Mars.

[3] Data supplied by JPL