특별강연

Flight Test of a Moon Lander

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1. Korean Small Moon Lander

In Reference 1, it was proposed that a small spacecraft be made to land on the Moon before 2015 using totally Korean technology. For convenience, this proposed mission will be referred to hereafter as Korean Small Moon Lander (KSML) mission. The purpose of this missionis to demonstrate technology readiness. As such, the lander will carry only the minimum or instruments: one television camera will send the pictures of the scenery around the lander.

According to this proposal, the KSML will be launched from a geo-transfer orbit (GTO) or a lunar transfer orbit (LTO) from a foreign launcher. The foreign launcher could be an independent launcher, available space for auxiliary payload (ASAP) of Arianne 5, or an equivalent. KSML will consist of two vehicles: carrier and lander. The carrier is battery-powered, and will be discarded after the release of the lander from it. The carrier will be guided by a star trekker. The lander will be guided by gyros and an electro-magnetic ranger. Communication between the lander and the control center on Earth will be via one of the several orbiters presently circling the Moon belonging to friendly foreign nations. Both the carrier and lander will have to be equipped with six-degrees-of freedom attitude control system (ACS) engines.

The mass of propellant needed ΔM in accelerating a spacecraft of mass M in zero gravity by a velocity increment ΔV is given by the well-known rocket equation

$$(M+\Delta M)/M = \exp[\Delta V/(gIsp)]$$

Here, g is Earth's gravity 9.8065 m/s^2, and Isp is specific impulse in seconds. To reduce ΔM, one must reduce ΔV and increase Isp.

In reaching the Moon, there are different navigational strategies. This arises because there is a point of zero gravity between Earth and Moon called Lagrangian Point 1 (L1). By passing through this point, the required ΔV becomes minimal.

Theoretically, from the LTO, one engine burn could place the vehicle into low lunar orbit (LLO). But this requires a perfect alignment of LTO with lunar orbit, both in position and velocity. Because the orbit in which the vehicle is placed at the time of separation cannot be expected to be aligned perfectly with LLO, multiple engine burn is needed. Well-executed multiple (of the order of 50) engine burns can make full use of the L1 energy minimum, and thus minimize the required ΔV.

But larger the number of burns, more chances for error occur. When one examines the record of past space missions conducted worldwide, one finds that significant portion of mission failures were due to navigational errors. Therefore, a compromise must be made between the desire for minimizing the required ΔV and minimizing risk. We plan to reach the Moon with about 10 burns from the time of the separation from the launch vehicle.

If the vehicle has a mass of 250 tons as proposed in Reference 1, the suitable thrust of the engine needed in this case will be of the order of a new hundred Newtons. If this thrust is delivered by four engines as proposed in Reference 1, one engine needs to have a thrust of the order of 100 Newtons. An engine of such a thrust level is presently being developed by Korea Advanced Institute of Science and Technology (KAIST).

The multiple engine burn be tested on the ground easily. Koreahas good past experience in navigation by star trekker. Therefore, one expects that the technological risk in reaching the Moon and placing the spacecraft in LLO is small.

But Korea has no experience in stagingthe lander and landing it on the Moon. Lander must be separated from the carrier, and the thruster on the lander must be fired to decelerate. Separation of the lander from the carrier is achieved by exploding the bolts that attach the lander to the carrier. The explosion produces a propulsive impulse. Because the impulses produced by these bolts cannot be expected to be exactly the same, a tumbling motion will start. Also, because both the Moon and the lander move, the axis of the vehicle constantly tends to deviate from the direction of vehicle's motion. If the vehicle has any rolling motion, precession will occur each time the thruster is fired. The ASC engines on the lander must be fired many times in order to align the axis of the thruster with the direction of lander's motion.

Thus, in LLO, the vehicle must execute the following steps:

1. Align the central axis of the carrier-lander assembly with the direction of LLO using he ACS engines on the carrier by referring to the coordinates obtained from the star trekker.
2. Initialize the gyros inside the lander.
3. Spin the vehicle around the central axis of the assembly using the ACS engines on the carrier.
4. Execute staging separation by exploding the bolts holding the lander to the carrier. The explosion should push the carrier far away from the lander.
5. De-spin the lander using the ACS engines on the lander referring to the gyro onboard the lander.
6. Align the axis of lander's thruster with the direction of its motion using the ACS engines on the lander referring to the gyros.
7. Fire the thruster on the lander to decelerate.
8. Repeat steps 6 and 7 until the vehicle reaches the altitude where the ranger on the lander can acquire the lunar surface coordinates.
9. Align the axis of the vehicle normal to the lunar surface using the ACS engines referring to the ranger information.
10. Fire the thruster to decelerate.
11. Repeat steps 9 and 10 until the vehicle touches downsoftly.

These steps obviously accompany risks. Failures occur in these steps rather often. For instance, the failure of the Space-X vehicle in early 2008 was caused by the collision of two separating stages. Apollo 2 and Fire 1 vehicles failed to initiatethe burn of the upper stages. For the Fire 2 vehicle, de-spinning was incomplete, and therefore a coning motion lingered on, which compromised the measurement. Some of the RAMC-series vehicles had similar problems also. In order to qualify the KSLM vehicle for flight, extensive tests must be carried out. Two types of tests are needed: flight test and ground test. Ultimate qualification is by a flight test. Ground test is necessary in the process of preparing for the flight test. The correspondence between the two types of tests must be established, so that one would have confidence in the ground tests.

2. Options of flight test

2.1. Sounding rocket

The most complete qualification test of the

KSML system would be to use a sounding rocket. A single-stage rocket with a thrust of the order of 10 tons could be launched from Goheung Space Center. The carrier-lander assembly will be its payload. While the rocket vehicle is still ascending, the payload will be separated. Sometime before the payload reaches its apogee, the steps 1 will commence. Because of the difference in speed and gravity, the test cannot simulate all aspects of the Moon mission, and cannot land softly. But still this test will be testing all steps of the lander mentioned above.

The main drawback of this option is its high cost: Koreamust first produce and test the 10-ton rocket vehicle. The qualification of the 10-ton rocket vehicle will require separate flights. In all, up to five 10-ton rocket vehicle may have to be produced. The total cost of the entire project will run to an equivalent of tens of million US dollars. In reality, such a vehicle can be used later for future versions of Moon landers. That is, may be up to 10 such rocket engines may have to be produced. If solid-propellant rocket is used for this purpose, each of these 10 rockets must be produced. Less expensive will be to use the methane-liquid oxygen (CH_4-LOX) engine made by Challenge and Space Company. If this engine could be dropped by a parachute and is reused, the total cost will be much lower than that of the solid-propellant system.

2.2 Full use of VOLNA

The burden of having to develop an entirely new sounding rocket system can be avoided by utilizing the VOLNA system of Russia. Russia is offering its obsolete submarine-launched inter-continental missile system named VOLNA for scientific research. The user is charged one to two million US dollars only per launch. The VOLNA system can deliver at least 700 kg payload to a speed of about 4000 m/s. The launch can be made at a port in Arctic Sea near Norway. The landing will be on the Far Eastern landing site.

The test article, i.e., the carrier-lander assembly must fit inside the payload bay of the VOLNA missile system. The compatibility of KSML with the VOLNA system must be worked out. Some compromise will have to be made in the design of the carrier and lander because of this. The cost of this project will be several million US dollars to Korea.

Another question exists regarding the procedure. Because the VOLNA system is a weapon, there will be several restrictions. The diplomatic and treaty relations between Republic of Korea and Russia will play a role here.

2.3 Participation in VOLNA-RadFlight

Currently, there is a proposal to conduct a flight experiment of a spacecraft using the VOLNA system for a different purpose. The project is proposed by European Space Agency. The purpose of this flight test is to test an Earth entry vehicle of mass of about 50 kg or so to an entry speed of about 11 km/s. This flight simulates the entry flight on return from the Moon or from other planets. Because radiation from the hot shock layer is the most prominent feature of the entry flight in this case, the project is named RadFlight. Because the VOLNA system can produce an entry speed of only about 4000 m/s, an additional stage thruster, i.e. the fourth stage engine, is needed. This thruster will be a part of the 700 kg payload. Who makes this thruster is not yet decided. Korea was invited to participate in this project.

If Korea can produce the fourth stage engine, then Korea will have a full control over the entry procedure, which is nearly the same as that for the Moon. Koreawill have to work closely with European and Russian engineers to carry out this mission. The cost of the entire project will be nearly the same as that of 3.2 given above. But an important merit of this option is that Europeans and Russians will be working with us. We could learn from them.

3. Ground test

3.1. Staging test

Because the above-described flight testsare costly, one cannot afford to carry out more than once. There-fore, before the flight test is conducted, there has to be a method to test the system in a ground-based laboratory. There must be three separate test facilities: a) staging test facility, b) approachtest facility, and c) terminal-landing test facility. In Figure 1, a staging test facility is shown schematically.

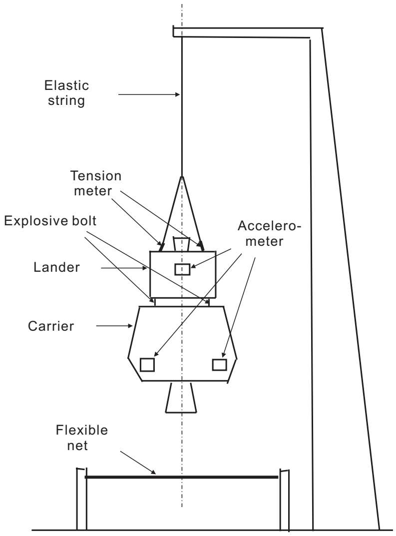

Fig. 1. Laboratory setup for staging test.

As shown, the carrier-lander assembly is suspended in air by an elastic string, which is attached to a hangout of a pole. The elastic string has four branches. On each of these four branches a tension meter is installed to measure the tension acting on the branch. The assembly is held with the lander on the top. The thruster on the lander is directed upward while the thruster on the carrier is directed downward. The two vehicles are joined by four explosive bolts. The Inside the two vehicles, several accelerometers are installed. Below the assembly, an elastic net is provided. Outside, there will be simulated star constellation for the star trekker to lock onto. There should also be several video cameras visually recording the event from several different positions and angles.

The test commences with the star trekker locking onto the constellation. The ACS engines on the carrier are fired in order to align the assembly axis with the hypothetical direction of assembly's motion. Then the gyros in the lander are initialized. The ACS engines on the carrier initiate a spin. The explosive bolts are broken by explosion. The carrier falls on the net. The ACS engines on the lander are fired to de-spin. After de-spin, the ACS engines are fired to align the axis of the lander with the desired direction. Then the lander's thruster is fired. The ACS engines on the lander fires again to align lander's axis in the desired direction. The test stops here.

All this while, the signals from the tension meters and accelerometers are collected into the main computer. Equation of motion is integrated using these data, and calculates what will happen in the actual Moon mission. The calculation results are displayed on a screen.

After the test is finished, the video data are analyzed. The coordinates and attitude of the two vehicles are determined as a function of time. The forces acting on these two vehicles are inferred from the history of the coordinates of the two vehicles. This history is compared with the history deduced from the instruments.

3.2. Descent test

The method of testing the descent procedure is illustrated in Figure 2. The lander is held by holding bars as shown. Elastic strings hold the two ends of the holding bar structure. When the elastic strings are long, the tensions in the two strings are almost equal regardless of the attitude of the lander. Tension meters and accelerometers can be placed at several strategic positions as were with the staging test setup shown in Figure 1. The lander will swing when the thruster is fired. Video camera will record the motion of the lander. One may provide a simulated lunar surface for the purpose of testing the ranger.

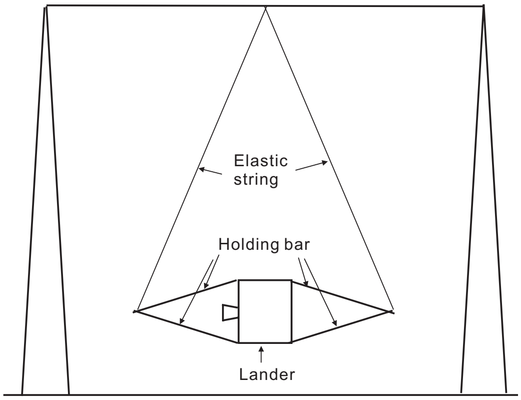

Fig. 2. Laboratory setup for testing the descent phase.

This setup will test the functioning of the gyros and the ranger and the interactions between the ranger, thruster, ACS engines, and the gyros.

3.3 Landing test

On the Moon, gravity is approximately 1/6 of that on the Earth. In order to test the soft-landing of the lander on the Moon's surface, the 0.17g environment must be created. Such environment can be created by a setupshown in Figure 3. As shown, one creates a partially-spherical dome around the lander. The center of this partial sphere must be the center of gravity. A ballast must be attached to the lander in order to bring the center of gravity to the desired point. Elastic strings are attached to the spherical surface. The elastic strings should be long. A pulley arrangement may be possible to make the strings longer. In this way, the force of the elastic string actings on the spherical surface is nearly constant regardless of the position or attitude of the lander. Because the radius of the partial sphere is constant, there is no net torque on the lander regardless of the attitude of the lander, as long as the angle of rotation is within the limits of the spherical surface. The elasticity of the strings is adjusted so as to provide a force equal to 0.83 g. This way, the lander feels 0.17 g regardless of its position and attitude.

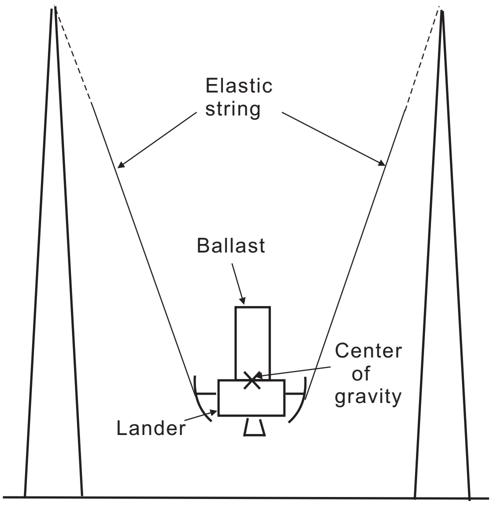

Fig. 3. Laboratory setup for testing the soft-landing of the lander.

In the beginning, the lander is sitting on the ground. With engine power, the lander will ascend. At a certain altitude, it will start descent. The ranger in the lander will start its function. The ACS engines and the thruster will fire in order to perform a soft-landing.

4. Concluding Remarks

Landing an unmanned spacecraft on the surface of the Moon involves many risky maneuvers. Flight test must be made before the mission. There are three possible options open to Korea: testing all aspects using a sounding rocket developed in Korea, and two different ways of using the VOLNA launcher of Russia. Prior to the flight test, ground test can be made using three different facilities.

References

1. Park, C., "A Roadmap to the Moon," paper to be presented at the 2008 Fall Confer-ence, Korean Society of Aeronautical and Space Sciences, Jeju, November 2008.