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Design and Simulation of Lunar Soft Lander

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ABSTRACT

In this paper, dynamic simulation and analysis for designing the soft landing of a lunar lander is focused. The primary objective of the lunar lander is to land safely on the surface of moon, without causing the lunar lander to topple and must attenuate the landing loads to preclude damage to the lander structure. The dynamic structural model of lunar lander is modelled and simulation described on Multi-body Dynamics software MSC ADAMS is discussed. The lander has important features of spring and damper system as shock absorber on the primary struts for energy absorption. To obtain the safe landing, various configuration design parameters are considered such as coefficient of friction, initial touchdown vertical and horizontal velocity components, lunar slope and crushing force of energy absorbing material in the leg struts. Effects on vehicle landing stability due to variations in vehicle velocity, orientation and the surface slope are discussed.

Keywords: lunar lander, dynamic simulation, spring and damper system, landing gear, crushing force.

1. INTRODUCTION

In recent years, lunar exploration has increased in order to utilize the lunar resources for mankind. For the purpose of exploration, a soft landing of lunar module is necessary. The orbiting module and lander are assembled together and maneuvered to a lunar parking orbit. Subsequently the lander is separated from the orbiting module and de-boosted for a safe descend to moon using precise guidance, navigation and control sub system. LAM engines equipped with lan- der are used to reduce its forward and descent velocities further for achieving the specified touchdown velocity. A soft landing system consisting of four land- ing legs with energy absorbing cartridges permit a stable and smooth landing on lunar surface. The four landing gear assemblies consists of a primary strut attached with a footpad at its lower end, two secondary struts and deployment truss. As impact force acts on the lander legs causes changes in the behavior of lander [1]. Dynamic analysis is necessary to analyze this behavior. To reduce the shocks, energy dissipation such as A1 honeycomb or spring and damper system can be placed in primary struts, secondary struts and beneath the footpads. The forces acting on the lunar lander during landing are from the landing gear system, the reaction control system, the descent-stage rocket engine thrust, and gravity. Forces acting on footpads are due to forces from the landing gear struts and from the landing surface [2]. This may goes to nonlinear analysis and the vehicle is idealized as an arbitrary rigid body. Inverted tripod landing gear style arrangement is used to attach primary struts and secondary struts with spheri- cal joints. The landing gears are made up of telescoping struts and connect the vehicle structure with footpads that contact the landing surface [3]. The foot- pad is design as a quadrant sphere because, force should transmit through the spherical joint of footpad. Vehicle landing stability mainly depends on variations in vehicle velocity, orientation and slope of the lunar regolith.

In the case of soft landing, elastoplastic deformation of landers buffer mate- rial are used to absorb impact energy of landing. The primary means of energy dissipation during landing are elastic deformation in primary struts, friction between footpad and lunar regolith. To support the landing stability of lunar

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lander, landing dynamics analysis has been widely researched [4-6]. The lander's legs must be designed to preclude damage to the lunar module at the time of touchdown and bring it to rest in an upright attitude. Because of uncertainty regarding the nature of landing sites on the lunar surface, it is necessary to consider very general conditions of topography and composition of the landing surface. Telescoping of a strut is resisted by forces which represent the effects of an aluminum honeycomb shock absorber mounted in the strut and the effects of overall system elasticity and damping. The landing structure must withstand and limit the force of landing. The Multi-body Dynamics software such as MSC ADAMS and SIMPACK are widely used for soft landing dynamic simulations of landing gears [7]. Components present in the landing gears are modelled as flex- ible materials. To analyze the dynamic soft landing impact of lunar lander, both the flexible models and transient dynamics are combined using MSC PATRAN and MSC DYTRAN [8]. It is essential to understand the stability analysis of lunar soft lander at the time of touchdown to assure proper functioning of such landing gears.

The system must maintain the structural integrity in order to assure stabil- ity by absorbing impact energy generated during touchdown. In this paper, a conceptual design of the soft landing system proposed for the lunar mission is modelled and analyzed the simulation in MSC ADAMS. Under different conditions, design parameters analysis has been observed and the soft landing dy- namics is analyzed. Landing correlation between analytical and theoretical data is presented. When the footpad is interacting with the landing surface material, a force acts on the foot and the shock absorbers may stroke. During landing the energy dissipation are elastic deformation and friction in the primary and secondary struts because of flexibility in lunar lander [9]. The force exerted on the footpad by the landing surface is assumed to be a function of the position and velocity of the foot. When the footpad is not interacting with the landing surface, the leg is assumed to move as a rigid extension of the body.

2. STRUCTURAL CONFIGURATION OF TOUCHDOWN DYNAMIC MODEL

The lunar module consists of ascent stage and descent stage, both stage func- tions as a single unit. The descent stage serves as a carriage, landing body and launching platform. The lunar module is treated as an arbitrary rigid body to which there are attached up to four landing gears. Each landing gear consisting of three struts in an inverted tripod arrangement. The descent stage requires larger propellant load because descent engine is much larger than the ascent engine. Inverted tripod landing gear style arrangement is used to attach primary struts and secondary struts with spherical joints. The primary struts outer cylinder is attached to the upper end of lunar body by universal joints. Secondary strut top end is attached to the bottom end of lunar body by universal joint and bottom end of secondary strut is attached to the footpad by spherical joint. The crushable footpads are hinged at the apex of landing leg, as shown in figure 1. The footpad is designed as a quadrant sphere because force should transmit through the spherical joint of footpad. The landing gear is an essential structural component of a lunar lander. At touchdown, the kinetic energy has to be ab- sorbed by the system in a controlled manner. In order to allow deployment of a rover, the system also has to support the static load of the landing module in an upright position. Each landing gear footpad is allowed three degrees of freedom in translation.

Landing impact is attenuated to load levels that preserve the lunar module structural integrity. The design and location of the secondary strut with respect to the primary strut allows the lunar module to land under two conditions. The module can land when the lunar module is moving laterally over the lunar surface or land on uneven surfaces. The landings legs are in the stowed configuration with the help of a retention system during the ascent phase of mission to meet the envelope constrains of launch vehicle. The legs are deployed by means of a release system on command before touchdown. Hexagonal honeycomb cylinders exhibit excellent energy absorption characteristics (constant load over the entire stroke) and are stable in vacuum environment. The kinetic energy available with the lander at landing is dissipated through crushing of honeycomb [1]. The honeycomb is made in cartridge form with hexagonal tubular cell

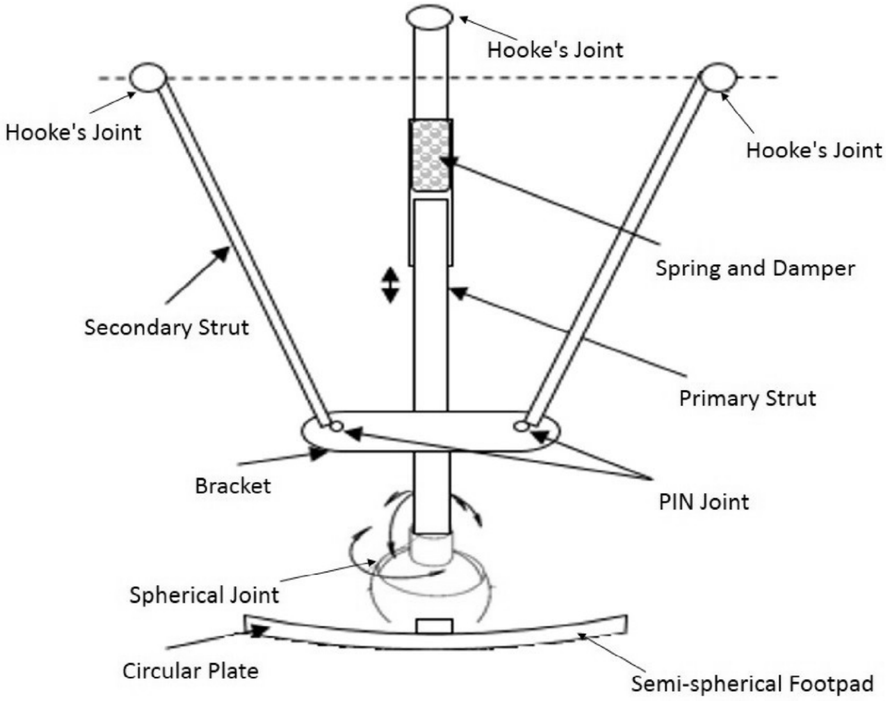

Figure 1: Landing gear configuration

construction. In this design the energy absorption system is provided in the primary strut only. An additional attenuation system can be placed on the bottom of the footpad to limit the landing loads on the footpad for varying lunar soil characteristics. It has a curved bottom with energy absorption material. This is also helps in reducing the stroke of primary strut and limit the penetration of leg into lunar regolith. The desired crushing force levels of honeycomb shock absorber can be obtained by varying the core cross-sectional area and the skin thicknesses [5]. The core can be stroked over 80% of its initial length before bottoming and the crushing behavior is unaffected by longterm exposure to the interplanetary environment.

One uplock assembly is attached to each landing gear assembly. It consists of a fixed link which is attached between the primary strut and the descent stage structure, and two end detonator cartridges in a single case. The fixed link holds the landing gear, while the cartridges when detonated holds sufficient energy to serve the fixed link. Connecting linkage and two clock-type deployment springs are the assembly of down lock mechanism and deployment. The truss connecting the secondary struts and descent stage structure, comprises two side frame assemblies separated by a cross member. Through the connecting linkages deployment springs are attached indirectly to the side frame assemblies. Static struts are rigid bodies protruding from the lunar module. Dynamic struts have the capability to extend from a collapsed state to a deployed state and lock themselves for landing position.

3. DESIGN METHODOLOGY AND SIMULATION MODEL

Parameters and structures of solid model of lunar lander is modelled and sim- ulated on multibody dynamics software MSC ADAMS. This software improves the efficiency and enables early system level design validation. Along with exten- sive analysis capabilities, it is optimized for evaluate and manage the complex interaction between interlinkages including motion, structural joints and controls to better optimize product design for performance. Two of the secondary strut members of inverted tripod landing gear form the rigid lower strut. This lower strut is mathematically treated as a single, rigid link rotating about the leghinge axis. It connects the lower hardpoint to the footpad pivot. This link is capable of carrying a moment in the plane of the lower strut. Load and forces computed by ADAMS simulation improves the accuracy of touchdown dynamic behavior of lunar lander by providing better assessment of how parameters are varying throughout the motion and operating environment. Simulation model of the lunar lander is shown in figure 2.

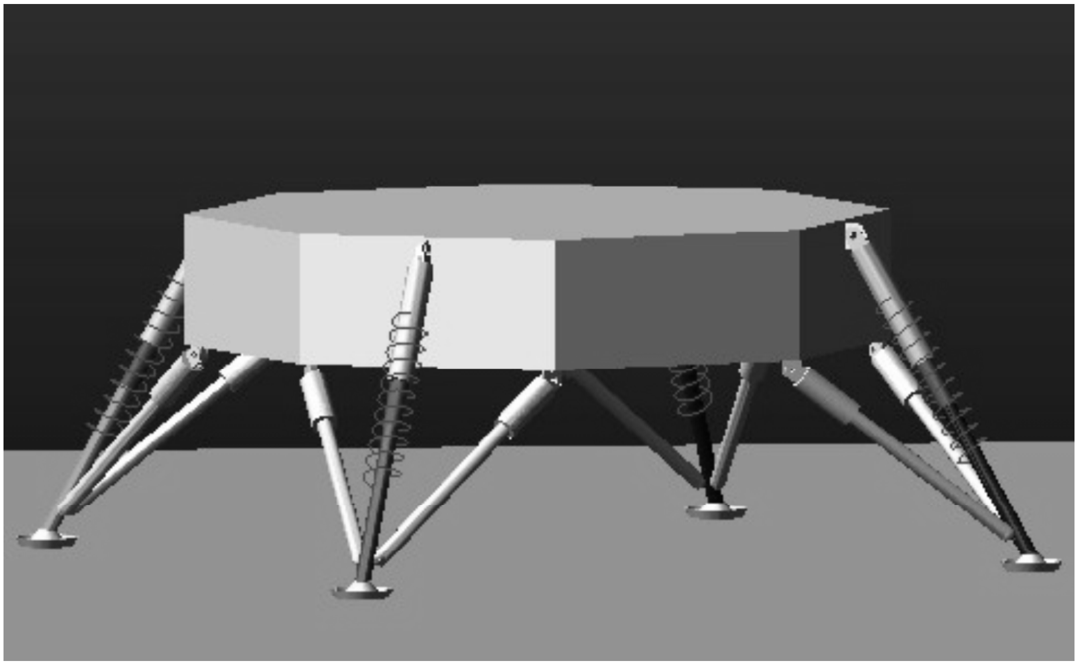

Figure 2: Lunar lander model to simulate soft landing

Stronger material for the landing gears is necessary due to the orientation of the struts and the potential for lateral loading. A large amount of lateral stress may be put on the strut during landing as there is a potential for the landing module to have a horizontal velocity. The lateral stress can also occur during static loading after the landing. At touchdown, large amount of kinetic energy is dissipated through the buckling of the spring and damper system. The forces transferred to the lunar module is reduced by the plastic deformation of the absorption material. The design of the static strut allows for the energy absorption system to be housed within the module reducing the overall volume of the module. The angle of the struts will help to support a degree of horizontal loading. During touchdown, the landing gears will be accelerated at an angle where its final position is less extended. The landing gears will drag inwards across the surface until the landing module has reached its rest position. The landing deceleration applied to onboard components is controlled by the crushing force levels of energy absorption material. The main strut attenuator must dissipate most of the touchdown energy, particularly in the event that the footpad can slide out across the landing surface depends on the dynamic friction of lunar regolith.

3.1 Landing Impact of Discrete Body

Forces acting on the idealized lunar lander structure during landing are vehicles landing gear system, reaction control system, descent-stage rocket engine thrust, rocket-engine-nozzle crushing loads and gravity. Forces acting on footpads are forces from the landing gear struts and landing surface. The direction of the friction force acting on either body block or footpad segment is such as to oppose the velocity of the body block or footpad. The vehicle geometry is completely described by input constants. The location of the upper hardpoint of the land- ing leg is defined by the angular inclination of the link connecting the lower and upper hardpoints to the longitudinal axis of the vehicle. In formulating the equations of motion for the system, the inertial coordinate system are considered in which X-Y plane forms the landing surface and the Z-axis is perpendicular and directed up from the X-Y plane. The rigid vehicle and landing gear footpad equations of motion are expressed in the inertial coordinate system. Where, $\ddot{X}$,

$$\sum F_x = m(a_x - g_x) = m(\ddot{X} - g_x). \tag{1}$$

$$\ddot{X} = \frac{\Sigma F_x}{m} + g_x. \tag{2}$$

$$\ddot{Y} = \frac{\Sigma F_y}{m} + g_y. \tag{3}$$

$$\ddot{Z} = \frac{\Sigma F_x}{m} + g_z. \tag{4}$$

$\ddot{Y}$, $\ddot{Z}$ are linear acceleration components of the vehicle center of mass. ΣF_x, ΣF_y, ΣF_z, are components of summation of forces acting on the idealized rigid vehicle w.r.t inertial coordinate system and m is the mass of the idealized rigid vehicle. The components of gravitational acceleration vector are g_x, g_y, g_z. The equations of motion of each of the legs are formulated, using their respective local coordinate systems, then integrated. These equations are uncoupled from the differential equations of the overall system. For describing the equation of motion in footpad, the force vectors applied to the footpads by the landing gear can be determined. Where, $\ddot{X}_{pn}$, $\ddot{Y}_{pn}$, $\ddot{Z}_{pn}$, are components of accelerations of

$$\ddot{X}_{pn} = \frac{1}{m_p}\left\{\sum F_{Xpn} - \frac{F_{dpn}\,\dot{X}_{pn}}{\sqrt{\left(\dot{X}_{pn}\right)^2 + \left(\dot{Y}_{pn}\right)^2}}\right\} + g_x. \tag{5}$$

$$\ddot{Y}_{pn} = \frac{1}{m_p}\left\{\sum F_{Ypn} - \frac{F_{dpn}\,\dot{Y}_{pn}}{\sqrt{\left(\dot{X}_{pn}\right)^2 + \left(\dot{Y}_{pn}\right)^2}}\right\} + g_y. \tag{6}$$

the n^{th} footpad and $\ddot{F}_{X\ pn}$, $\ddot{F}_{Y\ pn}$, $\ddot{F}_{Z\ pn}$, are components of resultant force on the nth footpad in the X,Y,Z directions (inertial coordinate system) respectively. The effective mass of each footpad is denoted as mp and Fdpn is the drag force on the nth footpad.

The positions and velocities of the footpads are obtained by integrating the above equations, when the nth footpad is in contact with the surface. If the nth footpad is not in contact with the ground, the positions and velocities of the footpad are calculated by assuming that, the footpad are rigidly connected to the vehicle. The initial conditions are the inertial position and velocity of each footpad at the instant the Z-coordinate of the respective footpad, $Z_{pn} \leq 0$. If a footpad leaves the surface after contact, the landing gear geometry is assumed to remain unchanged from the instant the footpad leaves the surface until it recontacts the surface. The primary struts have only compression type crushing and tension load are due to friction. The shock absorber in a strut is considered to produce simultaneously a force at the hard point and at the foot to which the strut is connected. The forces are considered to be equal in magnitude but opposite in direction and to be directed along the axis of the strut.

3.2. Stability Analysis

Landing module is manufactured and tested by dropping it from a specified height and surfaces which are having different slopes. Critical stability and land- ing gear impact force data were obtained by varying the model touchdown con- ditions and slope of the surface. The forces acting on the manufactured model during landing are gravity forces and landing gear strut forces. The landing gears were exposed to normal atmospheric contamination, ground-level winds and temperature. The maximum slope of the surface on which the lander can land safely is found out to be 21° .

Figure 3: Experimental model of Lunar lander

ADAMS simulation also proves the stable angle of landing is up to 21° which is then validated by testing based on earth gravity. The results are used to illustrate the effects of vehicle physical properties, approach orientation, and landing-surface slopes on landing stability, shown in table 1. These experimental data are also compared with theoretical results obtained from simulated landings.

Table 1
Lunar Lander Design Criteria

Parameter	*Experimental Model*	*Simulation Model*
Mass (kg)	28	480
Vertical Velocity (m/s)	3.9	3.5
Horizontal Velocity (m/s)	0	1.8
Ground Clearance (mm)	800	800
Gravity (m/s2)	9.8	1.6
Landing gear type	Inverted tripod	Inverted tripod
Stability (deg)	21	21
Coefficient of Friction	0.3	0.4

4. SIMULATION RESULTS AND DISCUSSION

Evaluating landing performance of a lunar soft-landing system using ADAM. Factors such as vehicle stability and contact force generated on each landing gear during touchdown are of prime importance. The forces acting on the lunar lander model during landing are gravity forces and landing gear strut forces. The landing gear strut forces are due to friction and to the deformation of the energy absorption system inside the struts. The axial stroking forces measured on the primary struts during landings are shown in figure 3.

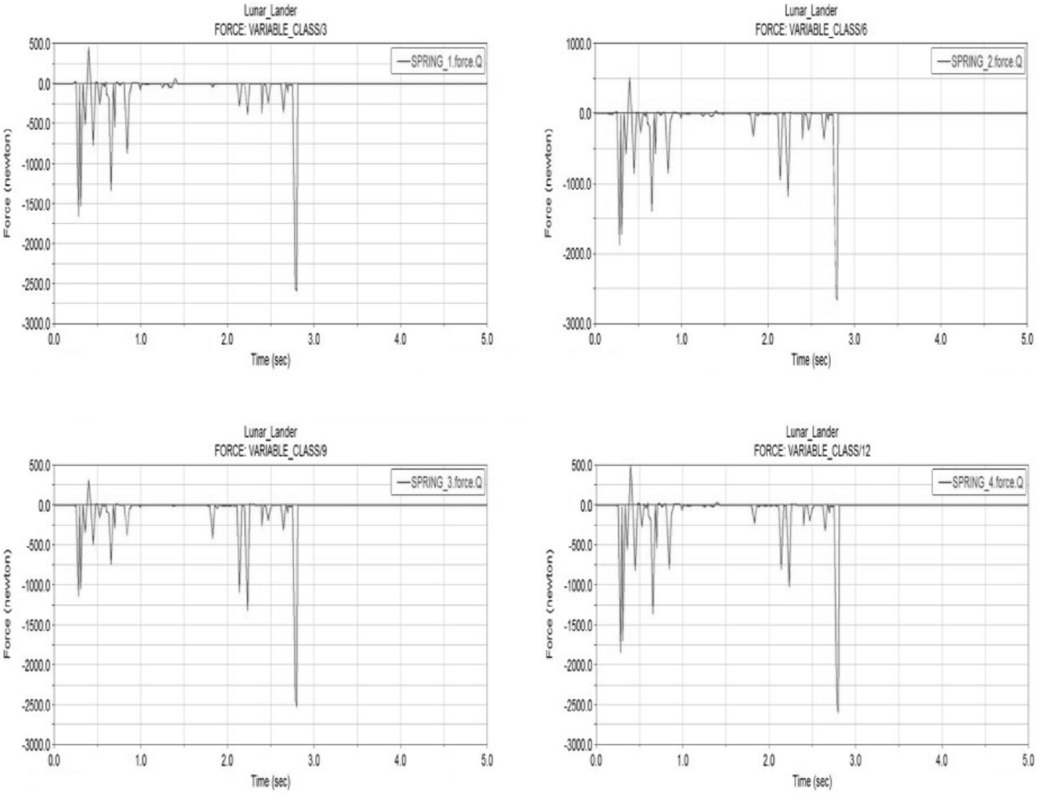

Figure 4: Landing gear strut forces on each landing leg

The spring constants are assumed to operate along the lunar body and support struts, stiffness of the vehicle’s body structure and elasticity between the footpads and their attachment to the struts. The footpad lifts from the surface and travels along with the lunar lander when the force normal to the surface becomes negative. Although the struts re-extend under a free return or no-load condition, there are intervals during where the footpad rests on the surface. To assure stability of the lunar module, the increased travel of the pads against the surface serves to keep the pads ahead of the center of gravity. This is important as the vehicle becomes unstable when the center of gravity passes over the foot- pads. The footpad load-stroke characteristics are similar to those of the primary strut. The footpad starts with zero crushing load before touchdown and strokes in tension or compression with a linear buildup in load at the time of touch- down. The shock absorber compresses because of elastic deformation until the load reaches the level at which crushing of the energy absorption system begins. Compression continues at constant load as the cylinder crushes. The effect of variation in angle of a lunar soft lander model while touchdown simulation is shown in figure 4.

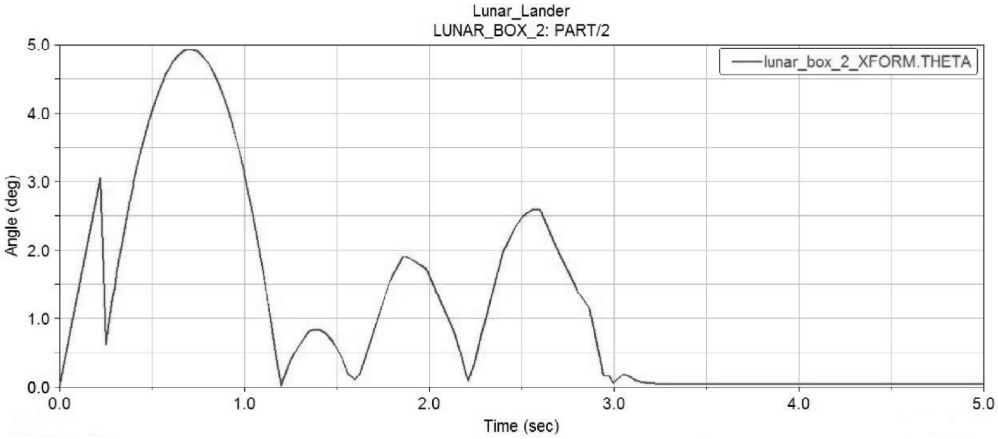

Figure 5: Effects on landing stability due to variations in lunar lander orientation

The developed equations are used to obtain contact forces generated at the touchdown of lunar lander. The touchdown stability boundary has been deter- mined as a function of the velocity components. The variation in velocity of lunar soft lander is illustrated in figure 5. The primary strut transmits the majority of the vertical load to the lander body. After maximum stroking of the land- ing gear struts occurs, the resulting vehicle motion will generally be rigid-body rotation about two adjacent landing gear footpads on the landing surface. The force experienced in each of the strut members, and the changing gear geometry during landing determine the stabilizing moments which act about the lander center of gravity.

5. CONCLUSION

This paper addressed the development of a procedure for computing the motions during soft-landing of a lunar lander. Lunar lander model with four inverted tripod style landing gear is built. The soft-landing dynamics simulation of the lunar lander has been developed and analyzed in MSC ADAMS. The simulations are focused on the influences on landing. Under different conditions, design param- eters the analysis has been observed. The generated output graphs provides the details about forces generated at each landing gears while touchdown and vari- ation in velocity of lunar lander with respect to time. The shock absorber in a strut is considered to produce forces directed along the axis of the strut. The research results shows that, most of the contact forces generated at the time of touchdown is absorbed by the energy absorption system present in the primary struts in each landing gear. Mathematical procedure of the differential equations which govern the motion of the rigid body part of the lunar lander is given. The simulation results shows that by increasing the initial horizontal and vertical velocities, probability of soft-landing of lunar lander is decreasing. The ideal- ization of the landing surface is developed and derived the equations of motion of the feet and forces generated by the interaction of the feet with the surface. The simulation results of the safe landing of lunar lander and landing correlation between analytical and theoretical data is presented. Discussed about the effects on vehicle landing stability due to variations in vehicle velocity, orientation, and the surface slope. Nature of force between regolith and foot pad is normal reac- tive forces. So the impact forces is determined by two body interaction between footpad and regolith.

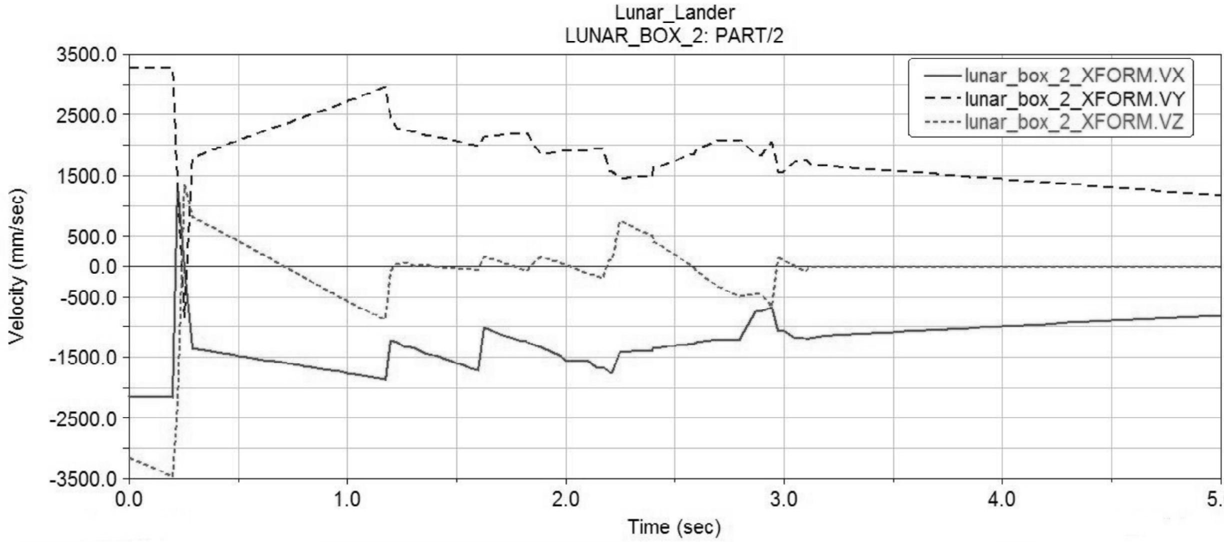

Figure 6: Effects on landing stability due to variations in lunar lander velocity

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