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DYNAMIC SCALING FOR EARTH BASED TESTING OF MARS TERMINAL DESCENT DYNAMICS

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ABSTRACT

The gravitational and atmospheric differences between Earth and Mars compromise flight-testing of Mars terminal descent dynamics on Earth. The inadequacy of Earth testing is particularly acute if aerodynamic induced oscillations must be nullified by the landing control system - as is the case for the 2003 Mars Exploration Rover (MER) mission. In this situation, full-scale Earth tests of the Mars flight hardware - even at high altitudes - will not recreate the Mars dynamics and may not represent a validation of the terminal descent system's performance. Performance validation is then relegated to analysis via dynamic model simulations. Fortunately, dynamic scaling laws can be utilized to design an Earth flight test - even a low altitude Earth flight test - that recreates the important interplay between aerodynamics and gravity as a means of validating these simulations. The purpose of this paper is to outline the derivation and imitations of a dynamic scaling law for Earth based testing of this type of Mars terminal descent system. The paper also summarizes the scale design of the MER Multi-body Dynamics Test and the MER Parachute Offloading Study as examples of low altitude implementations of this scaling.

NOMENCLATURE

A	*Aerodynamic Reference area, m^2*
C_D	*Coefficient of Drag*
F_g	*Gravitational Force, N*
F_a	*Aerodynamic Force: N*
G	*gravitational acceleration, m/s^2*
k	*Parachute entrained air mass coeff.*
L	*Characteristic Length, m*
M	*Mass, kg*
N_m	*Ratio of test mass to flight value*
N_t	*Ratio of test time scale to flight scale*
N_L	*Ratio of test length scale to flight length*
N_ρ	*Ratio of test density to flight density*
N_{mach}	*Ratio of test Mach to flight value*
N_{re}	*Ratio of test Reynolds number to flight*
N_V	*Ratio of test velocities to flight values*
N_F	*Ratio of test forces to flight forces*
N_k	*Ratio of test structural stiffness to flight*
N_I	*Ratio of test Moment of Inertias to flight*
T	*time, sec*
T^*	*Reference time, sec*
V^*	*Reference velocity, m/s*
ρ	*atmospheric density kg/m^3*
β	*angle of descent train off vertical, deg*

INTRODUCTION

Entry, Descent, and Landing (EDL) of a spacecraft on Mars is a problem of energy removal. The spacecraft, upon arrival at the edge of the planet's atmosphere, possesses giga-Joules of combined kinetic and potential energy relative to the surface. This energy must be dissipated to land the payload safely. Optimal EDL design is then the challenge of minimizing the mass required to accomplish this energy removal while maximizing reliability within project cost and schedule constraints.

Aerodynamic drag from a blunt entry capsule, followed by the deployment of a parachute, can effectively dissipate three to four orders of magnitude of the initial energy. Furthermore, the mass penalty to design these two systems to operate passively over the expected range of environmental uncertainties is not severe. However, for the thin atmosphere of Mars, the remaining energy associated with parachute descent is substantial. An energy absorbing touchdown system that dissipates this kinetic energy at ground impact could be designed but if impact loads to the science payload must be limited, the resulting touchdown system would include significant mass and volume

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penalty. A propulsive terminal descent system, in conjunction with a less capable hazard tolerant touchdown system, presents a more mass efficient solution. The addition of this propulsion system, however, necessitates the introduction of sensors and closed loop control laws to handle environmental uncertainties. To assure this additional system is reliable, Earth based field tests are required.

The MER mission EDL system begins with a blunt capsule hypersonic entry followed by a supersonic parachute deployment. After parachute deployment, the heat-shield is jettisoned and the lander deploys on a bridle from the backshell. The resulting descent train is a three body system comprised of parachute, backshell, and lander as shown in Figure 1. The backshell element of this descent train contains three vertical solid rockets in conjunction with three horizontal solid rockets whose role it is to decrease the vertical and horizontal motion of the lander just prior to ground impact. This combination of rockets assures the lander's impact velocity is within the capabilities of the lander's airbag touchdown system. A radar altimeter, descent imager, and an inertial measurement unit (IMU) supply data on motion of the descent train to control algorithms which determine the propulsive control action required just prior to touchdown. Control action in this case is the firing of the vertical and selected horizontal rockets. An Earth based test was desired which exhibited as close as possible the interaction between aerodynamics and gravity expected on Mars as a means of validating the associated control laws against realistic three-body pendulum dynamics.

Dynamic scaling laws for terrestrial aerodynamic systems have been studied and used to design scaled tests for many decades[1]. These tests enable controlled examination of complex dynamic phenomena such as aircraft spin[2] and parachute inflation loads[3]. Since most aerodynamic problems are both flown and tested on Earth, there has been little need to extend these scaling laws to include gravitational differences between the test and flight environments. Space missions that include landing on other planets - with atmospheres - present the only application. Henrich[4], and Barton[5] have examined scaling issues relative to Mars, but their efforts focused on parachute opening dynamics. In addition, previous Mars landers such as the 1976 Mars Viking mission relied solely on engine thrust for terminal descent so such an aerodynamically scaled test was unnecessary to validate that system. The terminal descent system for the MER mission, however, does rely on knowledge of the aerodynamic interaction of the descent parachute with the 2-body pendulum suspended masses to validate the system's performance. Thus, the present work represents the first large-scale field-testing for a Mars flight mission utilizing these dynamic scaling laws.

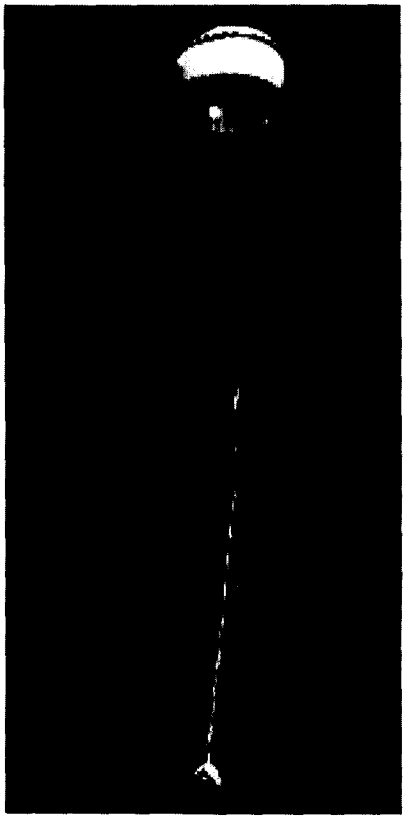

Figure 1: Mars Exploration Rover terminal descent configuration.

The objective of this paper is to present the derivation of dynamic scaling laws for Earth based testing of Mars terminal descent dynamics. Results from a dynamic simulation of a multi-degree-of-freedom Mars case are compared to the Earth scaled case. Examples of two low altitude dynamically scaled tests conducted by the Mars Exploration Rover Mission are summarized. This work has application to design and testing of future planetary landers.

DYNAMIC SCALING LAW

There exists numerous ways to derive the dynamic scaling law. For brevity, the present derivation will begin with Newton's second law in one dimension for a single point mass m of reference length L undergoing forces from gravity F_g and aerodynamic drag F_a.

$$F_g - F_a = m\,a$$

or

$$mg - \frac{1}{2}\rho V^2 C_D A = m\frac{\partial V}{\partial t}$$

where ρ is atmospheric density, V is velocity, C_D is the vehicle drag coefficient, and A is the reference aerodynamic area.

If we now define dimensionless Velocity *as*

$$\bar{V} = \frac{V}{V^*} \quad where \quad V^* = \sqrt{\frac{2mg}{\rho C_D A}}$$

and dimensionless time as

$$\bar{t} = \frac{t}{t^*} \quad where \quad t^* = \frac{L}{V^*}$$

the equation in dimensionless parameters becomes

$$\left(1 - \bar{V}^2\right) = \left(\frac{V^{*2}}{gL}\right)\frac{\partial \bar{V}}{\partial \bar{t}}$$

The solution of this first order nonlinear differential equation describes the motion of mass m in dimensionless velocity and time. The general solution is identical for all combinations of V^*, g, and L where the quantity (V^{*2}/gL) is constant. This quantity is the Froude number. Thus, the first form of the scaling law might be stated as

$$\left(\frac{V^{*2}}{gl}\right)_{flight} = \left(\frac{V^{*2}}{gl}\right)_{test}$$

by substituting for V^*, another form is

$$\left(\frac{m}{\rho L^3}\right)_{flight} = \left(\frac{m}{\rho L^3}\right)_{test}$$

Introducing a notation to describe the ratio of the scaled test values to flight values as

$$N_m = \frac{m_{test}}{m_{flight}}$$

$$N_\rho = \frac{\rho_{test}}{\rho_{flight}}$$

$$N_L = \frac{L_{test}}{L_{flight}}$$

The scaling law can then be written as

$$\frac{N_m}{N_\rho N_L^{\ 3}} = 1 \qquad (1)$$

This relationship, when met, assures the test system will experience the same balance of aerodynamic and gravity forces as exerted on the Mars flight article.

The derivation presented above for a single point mass in one dimension is a particularly uninteresting example since the only "dynamics" it can possess is a position time history. There would be little reason to conduct a scaled Earth test to confirm such dynamics. The scaling law in Eqn. 1, however, also holds for a multi-body system moving in multi-dimensions with other aerodynamic forces besides drag - as is the case of the three body system associated with the MER terminal descent configuration of Figure 1. In this complex case, terminal descent "dynamics" include angular oscillation of the three constrained bodies in numerous modes driven by the parachute's inherent motion or its motion under the external influence of wind sheers. While computational dynamic analysis routinely analyze the motion of systems of this complexity, such analysis inevitably includes numerous simplifying assumptions that must be validated via test.

Applications of the scaling law to design of an Earth test for a specific Mars flight are described below. Limitations of the laws – in particular as they relate to Mach and Reynolds number effects – are discussed next in the *Limitations of the Dynamic Scaling Law* section. Comments on High altitude Earth testing issues are then discussed.

APPLICATION OF SCALING LAW: LOW ALTITUDE TESTING

Application of this law to the design of a low altitude Earth based test begins with determining the ratio of atmospheric density available for test relative to the intended flight value. For example, if the test is attempting to simulate flight in Mars atmosphere at an altitude of –1.3 km (where the density is 0.014 kg/m^3) by testing at 2.5 km above sea level on Earth (where density is 0.962 kg/m^3), the ratio N_ρ is 68.7. For this case there are a family of mass and length ratio's which comprise a scaled test. Four of these options are presented in table 1.

N_m	N_L
0.38	0.18
1.0	0.244
68.7	1.0
1264	2.64

Table 1: Mass and length ratio options which solve Eq. 1 for N_ρ=68.7

The table reveals that one option is to select an Earth test in which the scaled test articles have the same mass as the Mars flight articles (N_m=1). If this is selected, the test articles must be approximately one quarter (N_L = 0.244) scale in size. In another option, the test articles can be the same geometric size as the flight articles (N_L =1),. For this option, the test article(s) must have a mass which is 68.7 times larger than their mars flight counterparts. These values reveal the first challenge to designing a scaled Earth test that recreates Mars flight. In particular, if the mass of the test article can be represented by the average density of the test article (ρ_{avg}) times its volume, and since volume varies like length cubed, Eqn. 1 can be rewritten as:

$$\frac{N_m}{N_\rho N_L^3} = \frac{N_{\rho,avg}}{N_\rho} = 1$$

Thus, the scaling laws dictate that the ratio of test article mass density to atmospheric density be constant in test and flight. Since the Mars flight density is very small relative to the test conditions, the test articles must have very high average mass density (i.e. be very massive for their size).

Application of the scaling laws also shifts the time scale of the test relative to flight. Introducing additional notation for ratios of time, velocity, gravity, and force as

$$N_t = \frac{t_{test}}{t_{flight}} = \frac{t^*_{test}}{t^*_{flight}} = \frac{N_L}{N_V}$$

$$N_V = \frac{V_{test}}{V_{flight}} = \frac{V^*_{test}}{V^*_{flight}} = \sqrt{\frac{N_m N_g}{N_\rho N_L^2}}$$

$$N_g = \frac{g_{test}}{g_{flight}}$$

$$N_F = \frac{F_{test}}{F_{Flight}} = N_m N_g$$

the four options presented in table 1 are now repeated in table 2 below for the case where N_ρ= 68.7 and N_g = 2.64.

N_m	N_L	N_V	N_t	N_F
0.38	0.18	0.67	0.26	1.0
1.0	0.244	0.8	0.304	2.64
68.7	1.0	1.6	0.62	181
1264	2.64	2.64	1.0	3337

Table 2: Ratio of velocity, time and force for four options where N_ρ=68.7 and N_g = 2.64

The table reveals that for the N_L = 0.244 geometric scale test where N_m = 1, motions in the test will proceed roughly three times faster than in flight (N_t = 0.304), but velocities will only be 0.8 of their Mars counterpart. For that case, all forces will be 2.64 times larger than then in flight. The table also reveals that if a test is desired to oscillate at the same time scale as Mars, N_t = 1, the test article must be 2.64 times larger and 1264 times more massive than the Mars flight article (and all forces will be 3337 times larger in the test). Such a massive scaled test is typically not feasible.

Design of the scaled test article must also consider mass properties. The ratio of moments of inertia N_I is simply

$$N_I = N_m N_L^2$$

If the dynamics of the system are influenced by elastic deformations, the scaled test article must also have the proper ratio of stiffness to the flight article. For a linear spring with stiffness k, the ratio N_k is

$$N_k = \frac{N_F}{N_L}$$

LIMITATIONS OF THE SCALING LAW

In addition to the challenges described above facing the design of a low altitude scaled Earth test to recreate Mars dynamics, there are additional limitations to the applicability of this law as described below.

The scaling law derived assumes the aerodynamic coefficients are invariant over the Mach and Reynolds number (Re) differences between flight and test. This presents one of the greatest limitations to the application of this form of scaling. An expression can be derived to reveal the difference in terms of the Mach and Reynolds Number using the ratio notation employed previously.

$$N_{Mach} = \frac{M_{test}}{M_{flight}} = \frac{N_V}{N_c}$$

$$N_{\mathrm{Re}} = \frac{\mathrm{Re}_{test}}{\mathrm{Re}_{flight}} = \frac{N_\rho N_V N_L}{N_\upsilon}$$

Where N_c and N_v are the ratios of speed of sound and viscosity that are 1.32 and 1.07 respectively for the case of Earth testing at 2.5 km of Mars at –1.3 km altitude.

N_m	N_L	N_{Mach}	N_{Re}
0.0007	0.02	0.045	1.0
0.38	0.18	0.50	7.74
1.0	0.244	0.61	12.5
14.7	0.6	1.0	22.4
68.7	1.0	1.21	103
1264	2.64	2.0	447

Table 3: Mach and Reynold Number Ratios

Table 3 reveals that in order to match Mach number, a 0.6 geometric scaling can be selected. Similarly, the improbable choice of a geometric scaling of 0.02 leads to a match in Reynolds number, but there exists no combination that simultaneously matches Mach and Reynolds number. Discretion must be used relative to the known dependence of aerodynamic coefficients to Mach or Reynolds number in determining if an acceptable test design exists. Fortunately, for the MER mission examples discussed here, both Mars and Earth Mach numbers are low subsonic and the aerodynamics are dominated by the parachute that is relatively insensitive to Reynolds number effects.

An additional limitation relative to scaling parachutes is fabric permeability. The aerodynamic performance of a canopy is dependent on fabric permeability. Scaling relationships could be derived to establish the proper permeability for the test canopy. Significant amount of work has been done on the scaling of parachutes for testing in different conditions on Earth[3]. This issue is beyond the scope of the present paper. For the MER examples presented below, the fabric permeability expected on Mars is very low, thus the test article parachute were constructed with very low permeability.

Finally, the scaling law defines an Earth test design for a specific Earth altitude to match a specific Mars altitude. The law can be used to define the appropriate variation in density with altitude to match the variation at Mars, however, since the atmosphere of Earth can not be adjusted, this aspect of the law is of little value. If the dynamics of interest are induced by significant altitude variation of density, it is not possible to create such a scaled Earth test. These laws pertain only to a specific point in altitude. However, if the dynamics of interest are not driven by the small altitude variations in atmospheric properties, as is the case for terminal descent, a useful test can be conducted which covers several km of altitude variation of Earth.

HIGH ALTITUDE EARTH TESTING

If resources permit high altitude testing, the ratio of test atmospheric density to flight, N_ρ , can be set to one. For the previous example where the Mars flight density was 0.014 kg/m3, the equivalent altitude at Earth would be 31,600 m or 104,000 ft

Again, Eqn. 1 can be used to select different test options for scale as was done in Table 1, except with N_ρ = 1. Of those options, the most interesting is N_L=1, which from Eqn. 1 results in N_m=1 and permits flight of the full scale Mars Flight Hardware.

The ratios in Tables 2 and 3 can be recomputed for this case to answer the question, `` What dynamics would be expected if the full scale Mars flight hardware were flown at this high altitude Earth condition?''. The results are presented in Table 4.

N_V	N_t	N_F	N_{Mach}	N_{Re}
1.62	0.61	2.64	1.34	1.75

Table 4: High altitude testing where N_ρ=N_L=N_m=1

The gravitational difference between Earth and Mars would then result in higher descent velocities. Oscillations of the full scale Mars hardware would proceed on a faster time scale then Mars. The forces on the hardware would be 2.64 times greater than expected on Mars and may provide a real limitation to this type of testing, depending on structural design loads.

Additional high altitude scale testing can be designed to match time scale, or Mach number, or Reynolds number without the infeasible model requirements noted at low altitude testing. However, the scaling law reveals there exists no high altitude test that recreates all aspects of Mars terminal descent.

MER MULTIBODY DYNAMICS TEST

The Mars Exploration Rover Mission required a low-altitude Earth test that recreated the relevant oscillations of that mission's three-body descent system during terminal descent. This test was used to validate the performance of the control algorithms that determined the firing of the horizontal solid rocket motor(s). The ratio of densities was the 68.7 value described in the above examples. A compromise between packaging volume for instrumentation and lifting capability of available helicopters constrained the feasible length scales, N_L , between 0.2 and 0.4. The N_L = 0.244 case where N_m=1 was selected simply because N_m=1 (where the mass of the test articles matched their Mars counterparts) offered some appeal to non-believers. A summary of the ratios associated with this selection is presented in table 5.

N_m	N_L	N_t	N_F	N_V
1.0	0.244	0.304	2.64	0.8

Table 5: MER Multibody Test Scaling Ratios

The MER three body descent train is shown in figure 1. It is comprised of a parachute, a backshell, and a lander. There exists no single parameter that describes the time history of the motion of this three-body system during terminal descent. It is a double pendulum suspended beneath a parachute. One useful dynamic parameter that describes the gross motion is the time history of the angle off vertical made by the line connecting the backshell body's center of mass with the lander's center of mass. The angle of this line relative to vertical is defined as β. Figure 2 presents a plot of this beta angle as a function of time for the Mars Flight system following a perturbation in the form of an applied impulse. The time history was computed by an 11 degree of freedom dynamical simulation. Figure 3 presents the calculation of the same variable but for the Earth Scaled version utilizing the ratios described in Table 5 and the appropriately scaled initial perturbation. While the character and amplitude appears to be identical, the time scales are shifted by approximately a factor of three. If the Earth test plot is re-plotted applying the time scale correction predicted by the scaling law, $N_t = 0.304$, the two plots lie on top of each other as shown in figure 4.

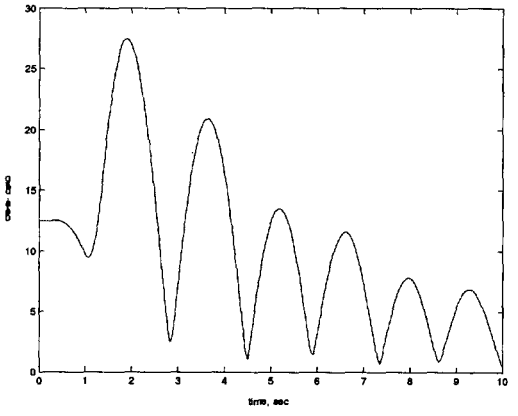

Figure 2: Earth test dynamic response

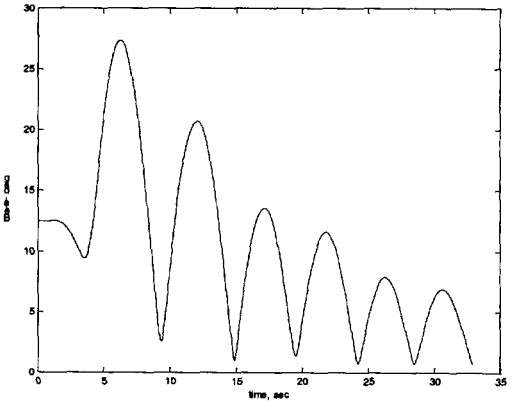

Figure 3. Mars scale dynamic response

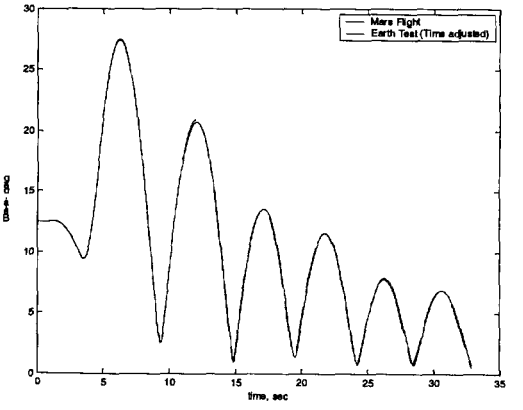

Figure 4: Comparison of Earth test and Mars flight response with Earth test time adjusted by $N_t = 0.304$.

Since N_L = 0.244, scaled representations of the parachute, backshell, and lander were designed and built for the Earth test. However, keeping the mass equal to the flight values while decreasing the size to 0.244 scale required selection of heavy materials for all articles and did not allow geometricly similar shapes for the backshell and lander. The parachute was constructed of 7.25 oz/yd2 nylon duck fabric with steel cables for suspension lines. The backshell included a large steel ballast slug and while it did not recreate the exact aerodynamic shape of the flight backshell, it did possess the appropriate drag area. The lander was a 530 kg slug of steel. Instrumentation - in the form of angle measuring devices at the parachute and lander bridle confluence points plus an Inertial Measurement unit (IMU) - resided on the backshell element. Since the expected descent velocities were approximately 60 m/s, the ballast section of the backshell with the entire lander steel slug were separated after the test period for free fall to the ground leaving the parachute to decelerate the backshell instrumentation to recoverable ground impact velocities.

The test was conducted at China Lake Naval Air Warfare Test Range in California using an Army National guard CH-54 helicopter. A detailed description of the results will be the subject of a subsequent publication. However, the measurements obtained during the 60 second test period displayed the expected vibrational modes as predicted by the dynamic simulation.

MER PARACHUTE OFFLOADING STUDY

When the MER descent train nears the surface of Mars, the vertical and horizontal rockets fire to further decelerate the lander to conditions within the airbag's capabilities. In addition to determining the proper time to fire these motors, the firing algorithm determines the time to cut the lander bridle. This cut effectively limits the duration of the fire and the deceleration delta-V applied to the lander. Determination of this bridle-cut time requires knowledge of the thrust expected from the vertical rockets plus the contribution made by the parachute during the rapid deceleration associated with the rocket firing.

A parachute carries with it an amount of entrained air mass[6,7]. The combination of the parachute's soft goods mass plus this entrained air mass represents the inertia of the system. If this combined inertia is very large, the parachute will deflate immediately when the rockets fire. Conversely, if the inertia is small, the parachute will continue to supply drag force during the rocket deceleration and it's effect must be included in predicting the proper bridle-cut time. For MER, the parachute's inertia is between these two extremes.

A test was desired to measure the effect of the parachute during the 3 g deceleration from the vertical rockets. The results would then influence design of the algorithm that determines bridle-cut time. The present dynamic scaling law provides guidance to design such a test. Table 5 presents the ratios selected for the test.

N_m	N_L	N_t	N_F	N_V
0.1	0.1	0.2	0.26	0.53

Table 5: MER Parachute Offloading Study Scaling Ratios

The test set-up involved release from a helicopter of a 0.1 scale parachute with 78 kg payload beneath it. (The combined backshell plus lander mass for Mars is ~780 kg., hence $N_m = 0.1$) The payload was comprised of a 3 kg instrumentation module plus a 75 kg ballast block hanging beneath the instrumentation module on a 4 m tether. The article was dropped from the helicopter at sufficient altitude to obtain terminal descent velocity prior to ground impact. When the ballast block did impact the ground, the suspended mass immediately decreased from 78 kg to just the 3 kg instrumentation module. This division of mass between ballast and instrumentation resulted in an accelerance to the instrumentation module whose value was similar to the that associated with the vertical rocket firing. The parachute's reaction to this rapid mass offloading was measured by an accelerometer and riser load cell. Numerous drops were conducted and the amount of entrained air mass could be derived from the measured accelerations and loads.

Figure 5 compares the measured load on the parachute bridle to predictions of that load which would result from differing amounts of parachute-entrained air mass. The results are presented in terms of a k value where k is the number of parachute volumes of air mass. The figure reveals that this parachute when undergoing this acceleration appears to have an entrained air mass equal to about twice of the enclosed volume of the parachute canopy.

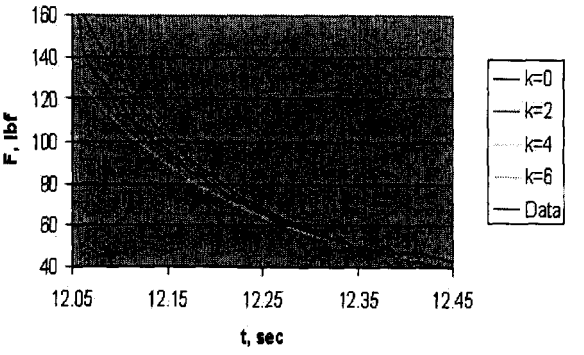

Figure 5: MER Parachute Offloading Study data, k=0 is top line, k=6 is bottom, data follows k=2.

SCALING LAW AND INTUITION

Finally, the scaling law can be used to assist the engineer in developing his own intuition when trying to understand complex phenomena in unfamiliar environmental settings. As an example, consider the challenge of designing an ejection scheme for a large lightweight instrumentation cover for a landed mars mission. Simply jettisoning such a low ballistic coefficient flat plate on Earth would result in a nearly chaotic motion as the plate cover flutters to the ground.

However, in the thin atmosphere of Mars, the aerodynamics could be negligible and the ejected cover might simply follow a ballistic path. How can the engineer be sure which motion would result. Expensive windtunnel testing could be conducted to establish the aerodynamic coefficients (static and dynamic) of the cover. These coefficients could be implemented in a six degree-of-freedom Monte-Carlo trajectory analysis. After much resource investment, the expected dynamics might be known. Conversely, the scaling laws could be employed to design a Mars equivalent of this cover for Earth testing. For example the scaling laws might reveal that the Earth scaled cover is actually 1/4 inch aluminum plate and it will immediately become clear that aerodynamics will be negligible.

CONCLUSIONS

The gravitational and atmospheric differences between Earth and Mars compromise flight-testing of Mars terminal descent dynamics on Earth. In some cases dynamic scaling laws can be utilized to design scaled Earth flight tests that recreate the important interplay between aerodynamic. Such a test can be used to validate the associated simulations or control algorithms. Several limitations exist when utilizing these scaling laws but useful tests were possible for the Mars Exploration Rover mission. The scaling laws also provide a means to allow engineers to apply their Earth based intuition to extreme environmental situations.

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