Opportunities and Limitations in Low Earth Subsonic Testing for Qualification of Extraterrestrial Supersonic Parachute Designs

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Abstract

Parachutes for Mars and other planetary mission often need to operate at supersonic speeds in very low density atmospheres. Flight testing of such parachutes at appropriate conditions in the Earth's atmosphere is possible at high altitudes (altitudes in excess of 100,000 ft). The NASA Viking mission to Mars qualified it's parachute through a series of four high altitude tests using balloon launched rocket propelled test vehicles. Three of these tests were at supersonic speeds (ref. 1). In subsequent Mars missions, the prohibitive cost associated with high altitude supersonic tests have led NASA to use low altitude (less than 10,000 ft) subsonic flight and wind tunnel testing for the design and flight qualification of the parachutes for its missions to Mars. This testing strategy has also been applied to other extraterrestrial missions such as Cassini/Huygens Titan probe and the British Beagle 2 effort (refs. 2,3). Designing and qualifying new parachutes in this way relies on the use of test data from the Viking (refs. 1,4,5), and other flight test programs (refs. 6-7) and heritage arguments. Specific assumptions used in this approach include:

The parachute drag coefficient at high subsonic and supersonic speeds can be determined based on low altitude flight and wind tunnel testing combined with heritage flight test data.

The parachute inflation dynamics including inflation time and critical inflation conditions at super sonic speeds will be similar to those observed during heritage flight tests (refs 1, 4-7) if the parachute and entry vehicle do not significantly differ from those used during the heritage testing.

Structural qualification of the parachute can be conducted with low-altitude flight or wind tunnel testing in the desired qualification loads are reached at full inflation.

Further extraterrestrial parachute applications such as NASA's 2009 Mars Science Laboratory, 2007 Mars Scouts as well as a potential return mission to Titan, face similar budget constraints and low altitude testing will most likely continue. To date no formal development of the rational behind this testing strategy has been given. This paper develops the arguments for and discusses the limitations of such a testing strategy. Examples of the current Mars Exploration Rovers mission will be used.

Symbols and Acronyms

BLDT Balloon Launched Decelerator Tests

LADT Low Altitude Drop Tests

C_D drag coefficient

C_{D_0} drag coefficient at some specified subsonic Mach number

EDL Entry, Descent and Landing

M Mach number

MEF Mach efficiency factor

DGB Disk-Gap-Band

MPF Mars Pathfinder Mission

MER Mars Exploration Rovers Mission

Introduction

The use of parachutes for aerodynamic deceleration during entry and decent into the atmosphere of an extraterrestrial body has historically always involved the supersonic deployment of the parachute, typically in very low density atmospheres. For Mars exploration, for example, the conditions for Viking and Mars Pathfinder deployments are similar to earth atmospheric conditions at 120,000-160,000 ft. This said, issues of real gas behavior and the density and temperature of the earth atmpshere mean that the only truly accurate test of a parachute supersonic Mars parachute system occurs on Mars. Clearly we can not fly to Mars just to test whether we can fly to Mars. The qualification of supersonic parachutes for extraterrestrial flight *must* be "an adequate compromise" between risk and cost. This compromise invokes the flight test (refs 1-7) and flight reconstruction data from previous missions and test efforts through a "heritage" argument. What is heritage and how far it can be stretched are then points of discussion or debate.

To bolster heritage arguments testing is conducted on earth. This testing can be used to anchor some of the behavior of a parachute design. But how this testing is extrapolated into the Mars flight conditions is a point for some careful consideration. There may exist low cost earth tests whose results may give misleading or incorrect information if not interpreted correctly. Below we discuss the three major points of parachute qualification and how earth tests may be leveraged to help in the qualification. We then discuss "heritage" and give some opinions on what constitutes significant heritage and some of the "heritage traps" that the recent MER project has discovered. Finally we close with some recommendations on testing approaches for extra-terrestrial parachute qualification.

Performance Qualification

For purposes of atmospheric entry and descent the primary attributes of aerodynamic decelerator performance seem to be drag production and stability. The first is obvious for its energy dissipation and the almost ever-present desire to spend more time on the parachute to execute various EDL events. The need for a measure of stability of a parachute comes into play when a soft landing, sensor performance, vehicle reconfiguration or other requirement places a premium on a stable payload. The authors are not aware of any extraterrestrial application that has had the requirement of high stability placed upon the supersonic flight regime of a parachute system. Thus far for extraterrestrial applications (ref 2, 8-10) stability has been a concern only for subsonic performance. Below we discuss the qualification of these performance characteristics.

Parachute Supersonic Drag Coefficient

Two possible methods of characterization of the supersonic drag performance of a parachute in Martian, Titan or other extraterrestrial atmosphere are either supersonic subscale wind tunnel testing (at appropriate pressure) or by use of high altitude, supersonic flight tests. Both these techniques are relatively expensive. For this reason, the missions that have used DGB parachutes such as Cassini/Huygens, MPF and MER have exploited Viking data. The two main sources of data for the drag coefficient of DGB parachutes behind a blunt entry vehicle at supersonic speeds are the Viking wind tunnel tests (ref. 1,4,11) and the Viking Balloon Launched Decelerator Test (BLDT) flight data (ref. 12). Use of the existing Viking data has been undertaken by re-casting the parachute drag coefficient data in the form of a Mach Efficiency Factor, *MEF* (ref. 9). The Viking wind tunnel and flight test data indicates that the drag coefficient of its parachute was nearly constant for $M < 0.6$. Normalizing the Viking parachute drag coefficient data by the drag coefficient value at a low subsonic Mach number (e.g., $M = 0.2$) yields curves for the Mach Efficiency Factor (*MEF*) vs Mach number. These curves have a value of $MEF \approx 1$ for $M < 0.6$. Using an *MEF* curve defined in this way, the supersonic parachute drag coefficient of a new entry system can then be estimated from:

$$C_D(M) = C_{D_0} MEF(M)$$

where C_{D_0} is the parachute drag coefficient at some subsonic Mach number ($M < 0.6$, preferably $M < 0.3$). Thus, the parachute drag coefficient at supersonic speeds can be estimated based on data at subsonic speeds (either from wind tunnel or flight tests). Obtaining a single value of the parachute drag coefficient at subsonic speeds is significantly less involved than determining the supersonic drag coefficient for a range of Mach numbers. In applying this approach to the estimation of the parachute supersonic drag coefficient, the following underlying assumptions must be satisfied:

- The parachute is of the DGB configuration.
- The entry vehicle is a blunt body.
- The relative dimensions between the entry vehicle and the parachute are similar to those of Viking. Of particular importance are the ratio of entry vehicle maximum diameter to parachute inflated diameter, and the ratio of parachute trailing distance to entry vehicle maximum diameter.
- The value of C_{D_0} includes the effect of the entry vehicle wake.

These assumptions limit the applicability of this approach to decelerator systems similar to Viking when using an *MEF* curve derived from Viking data (*MEF* curves derived from other data will have similar limitations depending on the source of the data). Figure 1 shows *MEF* curves calculated from the Viking wind tunnel (ref. 11) and flight test (ref. 12) data. For both of these *MEF* curves the normalization described above was performed using the parachute drag coefficient at $M = 0.2$. The wind tunnel and flight data yielded the same drag coefficient at this Mach number, namely $C_{D_0} = 0.61$. As can be seen from figure 1, there is a significant difference between the *MEF* curves at supersonic speeds as determined from the wind tunnel and flight test data. Although the reasons for this are not clearly understood, it is suspected that differences in the fabric permeability (due to material and/or test conditions) may be a substantial contributor to this discrepancy. The Mars Exploration Rover (MER) mission considered the Viking data presented in figure 1, and arrived at the *MEF* curve also shown in figure 1 for entry/descent/landing (EDL) analyses.

The Mach Efficiency Factor approach to the determination of the supersonic drag coefficient offers substantial savings in time and cost by voiding the need for supersonic wind tunnel and/or flight tests. However, its range of applicability is difficult to quantify. The question of to what extent can the new system differ from that used to determine the *MEF* has not been settled. In addition, this approach may stifle the pursuit of new concepts and configurations since it encourages similarity with previous systems.

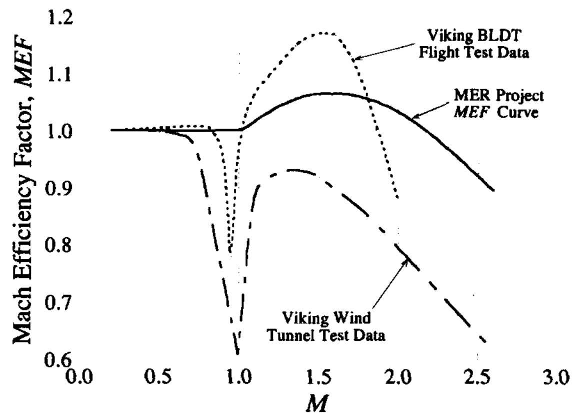

Figure 1 – Mach Efficiency Factor (*MEF*) curves.

Parachute Stability Characterization

One important characteristic of parachute performance for use in entry is the "stability" of the parachute (ref. 9,10,13). This refers to the trim angle of attach the parachute or the glide angle, from vertical, that the parachute system would take in still air. The premium placed on stability by both MPF and MER (refs. 9,10) existed because of a terminal descent system sensitivity to the pendulum motion that is frequently set-up with a parachute with trim angle of attack greater that 5-10 degrees. Test characterization of subsonic trim angle of attack and aerodynamic coefficients is possible in wind tunnel testing that incorporates low pressure. These test, although expensive compared to low earth ambient pressure wind tunnel testing, are not as difficult to perform or as expensive as their supersonic counterparts. Detailed description of the MER subsonic parachute stability characterization is found in reference 13.

Inflation Qualification

Inflation qualification of any parachute can be a difficult task. The difficulty in constructing an airtight qualification story with respect to inflation centers around the fact that causes of inflation failure (resulting in a what is sometimes called "squidding") are not well understood. Further, theory supporting a physical model to help yield insight into steps to take to prevent inflation failure is non existant. Inflation failure occurs when the parachute is in some partially inflated configuration and the mass flow into to the parachute equals the mass flow out of the parachute. This mass flow can come from both geometric and fabric porosity (fig. 2) the latter which must be calculated at the correct Reynolds number.

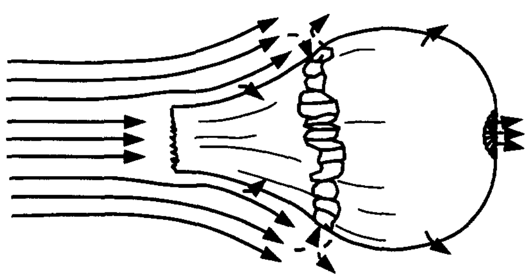

Figure 2 Possible Flow Into and Out of DGB During Inflation

The causes of the inflation "stall" may be related to many factors, but strongest among them are most likely the pressure distribution around the inflating canopy (a strong function of Mach number) and the fabric and geometric porosity. Juans right-up of ring sal inflation stall (14,15).

Unfortunately, that absence of a credible, tested theory on inflation failure makes the connection between subsonic testing in low earth atmospheres and supersonic high altitude (low density) inflation impossible. The MER project did not use successful low earth subsonic inflations as a component of their inflation qualification story. The inflation qualification story that was used for MER and which has the strongest case to back it up is one of heritage to already tested or flown configurations. In the case of MER the MPF flight, Viking BLDT and flight data and Pepp and Shape testing were used to construct the qualification argument. Figure 3 below shows a plot of the successful inflations of Viking and MPF DGBs over a range of deployment conditions.

Further details of inflation failure are beyond the scope of this paper but discussion of observations, possible scaling laws and phenomenology are found in ref (16-19).

It is the opinion of the authors, that low earth subsonic testing can not be used to contribute the qualification of a supersonic inflation. This places the stark choices before a mission considering the use of a supersonic parachute as a aerodynamic decelerator. Either fly a DGB parachute configuration very close to Viking or MPF/MER or be prepared to spend costly sums with high altitude (>140,000 ft for mars) testing.

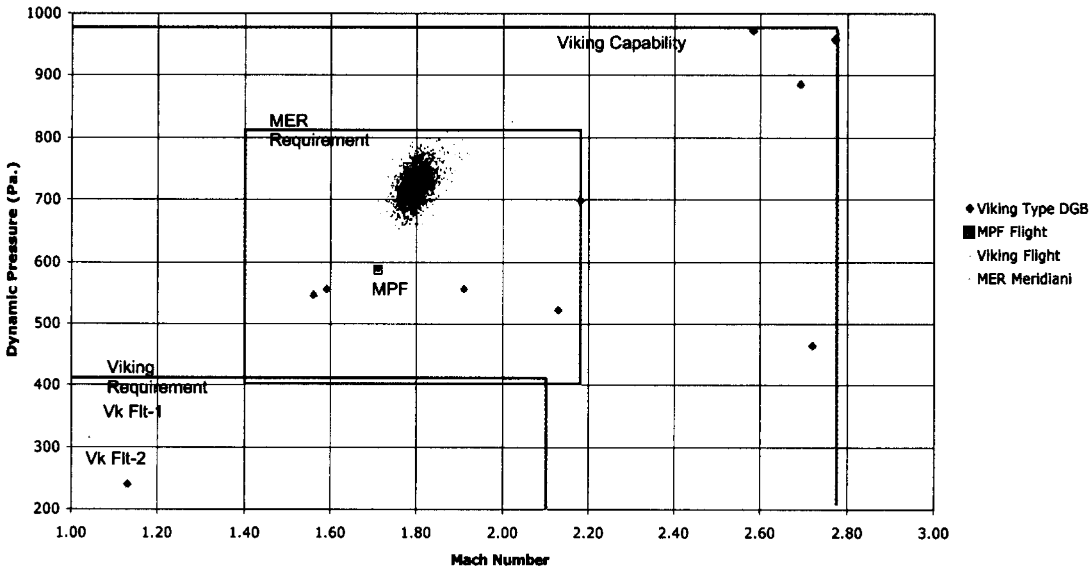

Figure 3 DBG Inflation Qualification Heritage

Strength Qualification

Structural Qualification of Parachutes

The structural qualification of the Viking parachute was conducted through a two-step test program in the Earth's atmosphere. In the first step, known as the Low Altitude Drop Tests (LADT) (ref. 20), the parachutes were subjected to an overload condition (30 percent above the Mars design limit load) while dropped from an altitude of approximately 50,000 ft. The final two tests of the LADT series were conducted at this overload condition and their success was taken as an indication of the structural capability of the Viking parachute. In the second step, known as the Balloon Launched Decelerator Tests (BLDT) (ref. 1), the parachutes were deployed behind a representative entry vehicle, at subsonic, transonic, and supersonic speeds, and at high altitudes (>90,000 ft). The successful structural qualification test of this series (known as AV-4) targeted a Mach number of 2.17 which was slightly higher than that expected during Mars operation, and a dynamic pressure that would yield a 16 to 30 percent overload condition (9 to 10 psf at peak load).

Subsequent American missions to Mars have only conducted structural qualification tests at subsonic speeds and low-altitude in the Earth's atmosphere, even though these parachutes were intended to operate at supersonic speeds on Mars. In these tests the approach used in the Viking LADT has been implemented – test to an overload condition at low-altitudes on Earth. Such low-altitude tests are significantly less expensive than supersonic, high-altitude tests such as the Viking BLDT. In undertaking a subsonic, low-altitude test program for the structural qualification of a parachute intended to operate at supersonic speeds in a low-density atmosphere, the following points and limitations must be kept in mind:

• In operation the parachute will undergo a near-infinite-mass inflation. This implies that the peak load will occur with the parachute fully inflated. Because stresses in the parachute are related to its shape, low-altitude subsonic tests should be conducted to yield peak load at full inflation. This is possible through either drop or wind tunnel tests (ref. 21,22). However, the parachute inflation state at peak load needs to be verified since it is possible to achieve the desired overload condition at less than full inflation, especially in drop testing.

• Even if the desired load is reached at full inflation during testing, the state of stress in the parachute will not be identical to that obtained in a supersonic opening. There are several reasons for this. First, the flow fields at subsonic and supersonic speeds will not the same - this will yield different pressure distributions. Next, inflation time for supersonic and subsonic deployments will be significantly different (often by an order of magnitude), with the supersonic inflation being faster. This difference in the inflation rate will have an effect on the unsteady aerodynamic forces, and the rates of stress at which the various materials are subjected. Finally, the fabric permeability at different atmospheric densities, atmospheric gases, and test conditions will have an effect on the stresses in the parachute.

• In deployments at supersonic speeds in low-density atmospheres, the Viking test and flight data suggests that the parachute will experience multiple load peaks of magnitude comparable to that at the initial peak load at full inflation. These multiple peaks are due mainly to elasticity effects and partial collapses of the parachute after the initial full inflation. In a subsonic low-altitude test on Earth the subsequent load oscillations after full inflation will be smaller in magnitude (not exceeding the load level of the first peak load). Thus, the effect of multiple load peaks on the parachute materials and construction is less severe in a subsonic low-altitude test on Earth as compared to a supersonic deployment in a low-density atmosphere.

• Aeroheating effects due to deployment at high Mach numbers is absent in subsonic tests. These effects are not significant for the Mach numbers at which the Viking BLDT were conducted. Thus, subsequent American missions to Mars have limited themselves to operating at Mach number not exceeding those used by the Viking BLDT tests. A future mission desiring to deploy a parachute at significantly higher Mach numbers will probably need to conduct a test program similar to the Viking BLDT.

A supersonic high-altitude Earth test for structural qualification is more representative of the actual operating environment for a parachute intended for operation at supersonic speeds in a low-density atmosphere. However, it should be noted that such a test is not an exact duplication of the expected operating environment. Differences in speed of sound at a given atmospheric density, composition of the atmospheric gas, and the acceleration of gravity, make an exact Earth simulation of a planetary parachute deployment impossible. These differences would need to be considered in defining the best simulation possible when planning a supersonic structural qualification test.

Heritage Arguments

Examples of heritage arguments (MPF v Vik, etc) examples of failures in heritage stretching and successes. Thoughts on what constitutes heritage.

Conclusions and Recommendations

Oputting all the above together...

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