LESSONS LEARNED AND FLIGHT EXPERIENCE FROM PLANETARY PARACHUTE DEVELOPMENT

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ABSTRACT

Recent planetary probe development experiences from the Phoenix Mars Scout and Mars Science Laboratory (MSL) parachute decelerator programs are reviewed. Particular attention is given to lessons learned from the development process and the testing techniques required to structurally qualify the parachute designs for flight. Limitations of these atmospheric tests are discussed and a rationalization for the flight qualification of the design is provided. Potential future parachute designs and the necessity for associated full-scale high speed testing are briefly examined.

Both Phoenix and MSL make use of Viking scaled disk-gap-band parachute designs and scalability issues encountered during the two efforts are discussed. In particular, MSL employs a 21.35 m reference diameter parachute which will be the largest extraterrestrial parachute ever flown. Full-scale wind tunnel testing of the MSL parachute revealed a band leading edge inversion failure mode that had never previously been observed in any test or flight deployment of a disk-gap-band parachute. The consequences of this new failure mode and its implications for the flight qualification are reviewed in the context of its intended flight regime.

The supersonic characteristics of the Phoenix parachute as measured in flight are compared to available full-scale terrestrial supersonic flight data as well as a Pflanz opening model that is commonly used to estimate supersonic parachute drag. The area oscillations phenomenon associated with Viking disk-gap-band parachutes is discussed in light of MSL's planned Mach 2.2 deployment and the potential consequences of extended supersonic operation required by the MSL entry timeline. This extended exposure to high speed flow necessitated additional testing in order to demonstrate structural margins against the increased parachute dynamics. The effect of the associated area oscillations on the entry body attitude and the potential risk due to excessive wrist-mode excitation are also assessed.

1. INTRODUCTION

The Mars Science Laboratory (MSL) mission will use a 21.35 m reference diameter (D_o) Viking scaled disk-gap-band (DGB) parachute as a critical component of its entry, descent, and landing (EDL) system. The MSL parachute will be deployed at speeds up to Mach 2.2 and must slow the entry body quickly in order to allow for heatshield separation and the timely release of the powered descent vehicle.

The MSL parachute is larger than any disk-gap-band parachute tested or flown in the supersonic, low dynamic pressure opening conditions that are required for use on a Mars surface mission. It was decided early in the MSL development process that qualification of the parachute via high altitude supersonic testing was cost prohibitive and would not be performed. Instead, a strategy was developed by the Jet Propulsion Laboratory (JPL) team to address the readiness for flight by dividing the parachute's function and operation into five phases: 1) mortar deployment, 2) canopy inflation, 3) inflation strength, 4) supersonic performance, and 5) subsonic performance. The qualification of each phase is addressed through test whenever possible, but also makes use of historic data in order to assess flight regimes that would otherwise require high altitude testing. It is possible to compartmentalize the parachute decelerator system (PDS) qualification differently, but this breakdown was determined to be the most practical and cost effective way to qualify the MSL parachute [1]. This same general approach has been used by all heritage Mars surface landers flown since Viking including: Mars Pathfinder (MPF), Mars Polar Lander (MPL), the Mars Exploration Rovers (MER), Beagle 2, and Mars Scout Phoenix (MSP). The parachutes for all of the NASA post-Viking missions to Mars were developed and fabricated by Pioneer Aerospace Corporation using similar materials and construction techniques.

The continuing quest to deliver heavier payloads to Mars is not without its price, however, as it has increased the demands made upon the parachutes required to slow the entry vehicle's rate of descent. The difficulties associated with this improved performance

are readily apparent in comparing the experiences from Phoenix, which successfully landed on May 25, 2008, and MSL, which is slated to launch in the fall of 2011.

2. LEARNING FROM OUR PAST

NASA commissioned three series of high-altitude, supersonic parachute tests in the late 1960's and early 1970's in order to develop the parachute technology required for planetary exploration. The three programs were: Planetary Entry Parachute Program (PEPP), Supersonic Planetary Entry Decelerator Program (SPED), and Supersonic High Altitude Parachute Experiment (SHAPE). A total of sixteen high-altitude supersonic flight tests were conducted during these three programs: eight with Disk-Gap-Band (DGB) parachutes, five with ringsail parachutes, and three with cross parachutes [2]. NASA's efforts culminated in the Balloon Launched Decelerator Test (BLDT) program which deployed four 16.1 m diameter Viking parachutes in high altitude terrestrial tests [3-8]. Three of these tests, AV-1, AV-2, and AV-4, were supersonic deployments.

A summary of opening conditions for all of the relevant PEPP, SHAPE, SPED, and BLDT test data is provided in Fig. 1 along with the four most recent flight conditions from MPF, MER-A, MER-B, and Phoenix, and the planned opening conditions for MSL. It is worth noting that the only parachute larger than 16.1 m ever tested supersonically was the 19.7 m DGB parachute from PEPP that was deployed at Mach 1.59 with a dynamic pressure of 555 Pa [9]; these are significantly different from MSL's Mach 2.2 and 750 Pa planned opening conditions for a parachute that is also 1.17 times larger.

While there is a rich history of DGB parachutes being used under Mars EDL conditions, it is likely that further high altitude testing would be required prior to the use of a supersonic ringsail parachute due to the limited number of data points available. One way to circumvent this issue is to use a smaller DGB parachute to slow the vehicle from supersonic speed and then deploy a ringsail parachute in subsonic conditions but this requires mass and timeline both of which are at a premium for heavier Mars surface payloads [10]. Nevertheless, a ringsail parachute offers an improved subsonic coefficient of drag (C_d~0.8) and hence lower terminal velocity over a DGB parachute (C_d~0.6). In the fall of 2004 a 33.5 m ringsail parachute was tested subsonically at high altitude with some mixed results [11,12].

Finally, the physics of high speed parachutes have one more trick to play which is that of aerodynamic heating. In addition to extremely violent parachute dynamics, deployments above Mach 2.7 are threatened by thermal and materials issues [2]. At speeds above Mach 2.7 it is likely that an inflatable aerodynamic decelerator (IAD) used as the first stage of a two stage system will prove to be more capable of handling the environment and producing the desired deceleration.

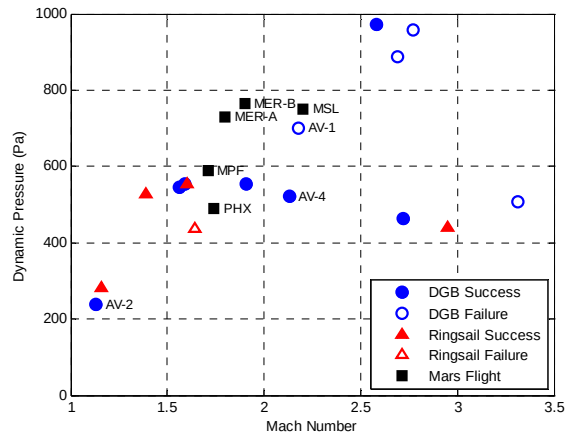

Fig. 1. Mach number and dynamic pressure opening conditions for historic test and flight parachutes designed for use at Mars.

3. THE PHOENIX EXPERIENCE

The Phoenix lander holds three very important distinctions that make it a unique and a highly valuable flight experience. The first distinction is that it is the only surface mission to Mars that has returned high rate inertial measurement unit (IMU) data. The Phoenix data were sampled at 200 Hz whereas MPF and MER were sampled at 8 Hz; as a result, the Phoenix data set is the only flight data that can accurately resolve the parachute dynamics during EDL. The second distinction is that the Phoenix parachute achieved a fully-opened geometry faster than any other supersonic parachute [13] thus serving as a reminder that the available test data are incomplete. MSL, by contrast, is expected to open relatively slowly based on the high altitude deployment of a 19.7 m parachute during the PEPP program [9]. The third distinction is that it is the only lander ever to be photographed during EDL. Through a fortunate set of circumstances and a determined operations team the HiRISE camera onboard the Mars Reconnaissance Orbiter (MRO) was able to image the Phoenix lander suspended from its parachute. A close-up view of this remarkable image is shown in Fig. 2.

The parachute drag force calculated using the IMU data returned from Phoenix is plotted in Fig. 3 for the first five seconds immediately following the mortar firing. Other representations of the same data set are

plotted and discussed in References 13 and 14. Aside from its rapid inflation, the other notable characteristic of the data in Fig. 3 is the unsteady nature of the drag force. In particular, since the mortar fired at Mach 1.7, the first 1.7 seconds are spent above Mach 1.5 where large drag disturbances are known to be present. These "area oscillations" are evident in the BLDT AV-4 data [6] shown in Fig. 4.

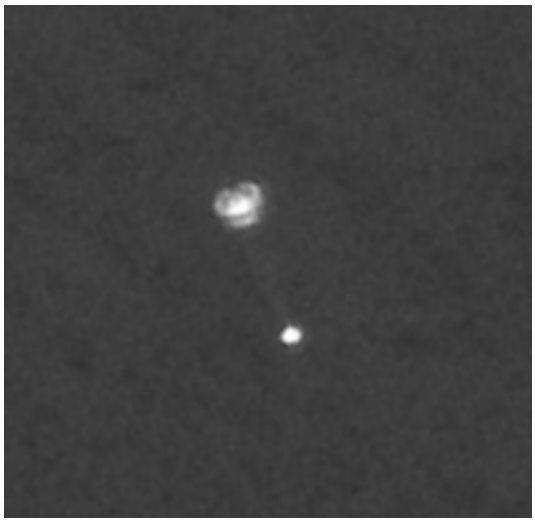

Fig. 2. Phoenix parachute and entry body during EDL at Mars as photographed by the HiRISE camera onboard MRO.

While at least one significant area oscillation is evident in Fig. 3 at 1.3 seconds after mortar deployment, it is evident from Fig. 4 that the conditions experienced by the Phoenix parachute are at the tail end of the more stressful and more violent conditions that are expected on MSL. As a result of this the MSL parachute carries a requirement for area oscillation loading that is new to this application. Note that, as stated previously, the area oscillations in Fig. 4 occur only above Mach 1.5; this characteristic was carried forward in determining the number of area oscillations required for qualification on MSL, whereas the load amplitude was bounded by completely collapsing and re-inflating the canopy during wind tunnel structural qualification [1].

One of the most important consequences of the unsteadiness of the parachute load is that it results in an excitation of the "wrist mode" of the entry body. The wrist mode is simply the rotation of the entry body about its center of mass in a rotational pendulum fashion with the parachute force applied at the triple bridle confluence point acting as the torque. If the parachute force variation acts in phase with the entry body motion then the wrist mode is amplified as was the case for Phoenix during the first four seconds following the mortar deployment shown in Fig. 5. Conversely the parachute can interact destructively and remove energy as is the case for the period from 4-10 seconds in Fig. 5.

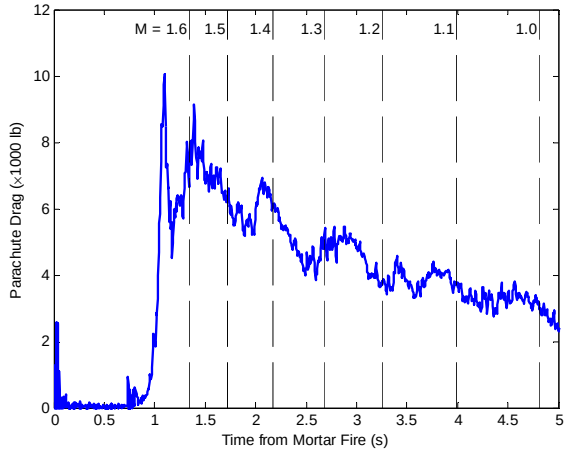

Fig. 3. Phoenix parachute drag force data immediately following parachute mortar fire. The Mach number is indicated as the vertical dashed lines.

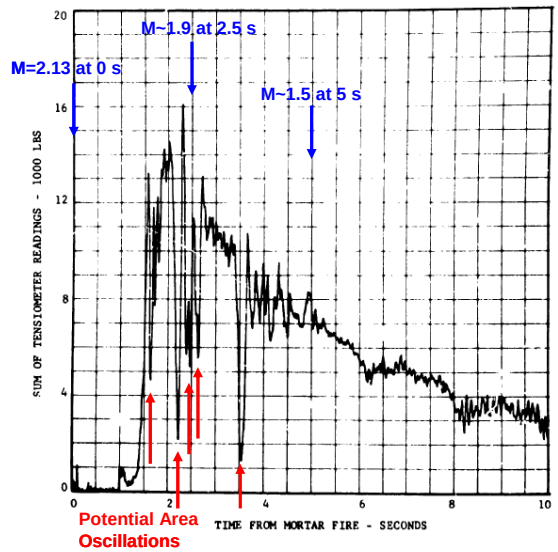

Fig. 4. Measured load history for BLDT AV-4 that shows unsteady drag with sharp drop-outs representing potential area oscillations at speeds above Mach 1.5.

Because parachute area oscillations increase at higher Mach numbers they will exacerbate the wrist mode and corresponding vehicle loads for MSL much more severely than was the case for Phoenix [15].

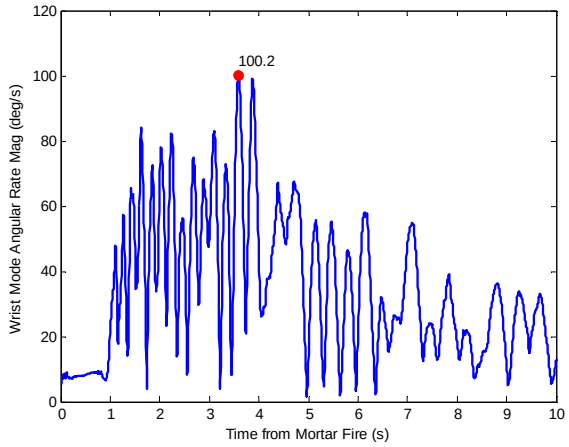

Fig. 5. Phoenix entry body wrist mode angular rate RSS magnitude following parachute mortar fire.

4. CHALLENGES OF STRUCTURAL TESTING

Although no supersonic tests were performed for either Phoenix or MSL it was still necessary to structurally qualify both parachutes for flight. The traditional way to generate loads in a parachute is through a low altitude atmospheric drop test. However, drop testing becomes increasingly difficult for larger parachutes as, in order to replicate the loading conditions encountered at Mars, the dynamic pressure must be matched with a fully opened parachute geometry; this set of conditions results in a high acceleration of the drop test vehicle which makes timing extremely important. This infinite mass loading requirement was OK for the 11.8 m Phoenix parachute as shown in Fig. 6, but was very difficult for MER's 14.1 m parachute and proved to be prohibitive for MSL's 21.35 m parachute due to the uncertainty in opening time.

Both MER and MSL relied on wind tunnel tests which were conducted in the 80'x120' test section of the National Full-Scale Aerodynamics Complex (NFAC) at NASA's Ames Research Center, Moffett Field, CA. The NFAC facility is the world's largest wind tunnel but, even with this distinction, when MSL's parachute was deployed it blocked 25% of the tunnel area and was only 15 feet from both the floor and the ceiling of the test section. During MSL's parachute development program a 23 m parachute was also flown in the NFAC tunnel but anything significantly larger would likely be very difficult to test. It is not just the diameter that is challenging but also the length of the parachute system which, in the case of MSL, extended beyond the normal test section resulting in the parachute opening in the diffuser section of the tunnel [16].

Fig. 6. Phoenix 11.8 m DGB parachute during a low altitude drop test.

Fig. 7. MSL 21.35 m DGB parachute flying in the NFAC 80'x120' test section. Note the two parachute handlers standing below and on both sides of the parachute.

The most important characteristic of testing in the NFAC wind tunnel was the ability to maintain a nearly constant dynamic pressure throughout the parachute opening event. The rapidly changing dynamics were an issue for Phoenix drop testing but one that was overcome through careful and then aggressive testing. Because the MSL parachute is so large (3.27 times the size of the Phoenix parachute) the uncertainty in its opening time is correspondingly large as well [17]. This uncertainty in opening time led to a rather spectacular drop test failure early in the MSL parachute's development phase.

Testing in the NFAC tunnel was not without its problems and led to the discovery of an unexpected feature of the MSL DGB parachute which was its susceptibility to an "inversion" under sea-level horizontally deployed conditions. An inversion occurs when the leading edge of one side of the parachute crosses in front of the leading edge of the opposing side and inflates with pressure applied to what would normally be the outside of the canopy. If the nascent inversion is strong enough then it will grow in a divergent fashion thus inverting the parachute resulting in a catastrophic failure. The inversion phenomenon was first observed on the second mortar deployed parachute at NFAC but was not adequately captured on camera until it occurred a second time during the eighth mortar deployment. A single frame from the high speed camera showing the incipient band leading edge inversion is shown in Fig. 8. A tiger team was formed to assess the risk to flight posed by these new observations and it was determined that they were the result of deploying the parachute horizontally [18] and were not characteristic of the supersonic flight conditions.

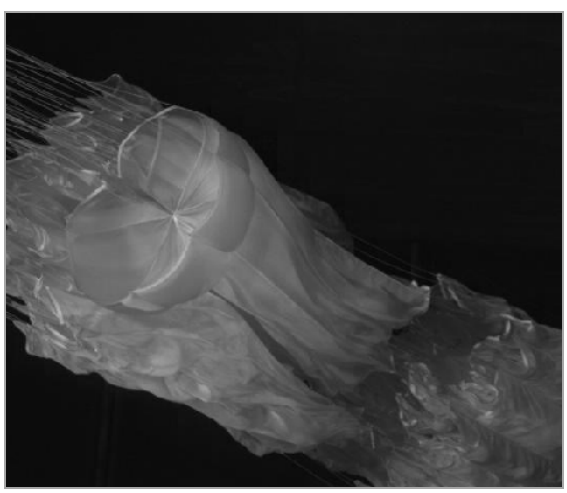

Fig. 8. Band leading edge inversion observed during the eighth mortar deployment test at NFAC.

5. OTHER GROWING PAINS

Parachutes are notorious for not scaling well and the change in size from MPF (12.7 m), MER (14.1 m), and Phoenix (11.8 m) to MSL (21.35 m) was no exception. Aside from the difficulties of structurally testing the parachute, there were a host of other scale related issues that consumed additional resources.

The MSL parachute pack was much larger than any other Mars parachute flown before it. This necessitated a much larger mortar and gas generator to propel the parachute away from the entry body [19]. The design and manufacture of the mortar had to be completely reconfigured from previous programs in order to accommodate the new volume requirements. A much larger gas generator was also required and it was found that the propellant efficiency did not scale linearly, thus requiring a number of additional tests to verify its performance. The parachute pack was, in fact, so large that the compression of the pack during the firing of the mortar resulted in a measureable degradation of the ejection velocity.

Because the MSL mortar is so large, the thermal protection system (TPS) lid that protects the parachute from the heat of Mars atmospheric entry also had to grow accordingly. Other missions had used a single sheet of aluminium or graphite composite to support the TPS but the MSL lid grew to the point that its construction required a honeycomb sandwich panel. The resulting ballistic coefficient was high enough that a re-design of the lid had to be undertaken to remove mass in order to prevent a possible re-contact between the lid and the inflated parachute.

Even the MSL parachute deployment bag mass grew to the point of becoming an issue. On Phoenix the deployment bag was small enough that it was retained at the parachute vent by a single Kevlar cord. On MSL, however, the number of restraint cords grew to 12; the cords were required to ensure that the bag did not damage the parachute during the expected supersonic area oscillations.

With the increased load the single riser and triple bridle legs grew to such that they could no longer be accommodated by a heritage confluence fitting approach and a new triple bridle confluence fitting had to be designed and tested. Because of the need to test in the NFAC wind tunnel the confluence fitting had to be demonstrated as being capable of withstanding 162,500 lb or 2.5 times the flight limit load. Testing the confluence fitting to this load required a specialized test set-up at the University of California, Los Angeles (UCLA).

Finally, the loads in the suspension lines of the MSL parachute had grown to the point that the Kevlar-29 material used on previous Mars flights would not fit through the meridional seams of the band and disk. This was solved by changing the suspension line material to Technora-221 marking its debut as a primary structural member on an extraterrestrial parachute. This resulted in yet another set of unplanned tests in order to qualify the Technora material for flight.

Finally, a series of 4% scale supersonic wind tunnel tests were performed to help further the understanding of the parachute's behavior at Mach > 2. These tests were also used to help refine computational fluid dynamics (CFD) and fluid structures interaction (FSI) computational models of the parachute [20,21]. This led to a better understanding of the parachute aerodynamics that can hopefully be leveraged in the construction of the next generation of extraterrestrial parachutes.

6. CONCLUSIONS

The high resolution data returned by the Phoenix lander supports the presence of parachute area oscillations for Viking DGB parachutes at speeds above Mach 1.5. The MSL parachute must be designed to withstand the more violent oscillatory environment associated with its planned function at speeds as high as Mach 2.2. The MSL entry body must be capable of handling the uncertainty in the loading that accompanies the higher Mach environment due to the excitation of the entry body wrist mode.

Drop testing of parachutes significantly larger than those used on MER or Phoenix is likely prohibitive due to the uncertainty in the parachute opening time and the need to achieve qualification loads at a fully opened state in order to simulate the near infinite mass conditions that will be encountered at Mars. Future missions may be able to avoid growing the parachute diameter further by switching from a DGB to a ringsail parachute but this will likely require additional supersonic full scale testing or a two stage parachute system to ensure that the ringsail will function properly in flight.

Growing a parachute's size can have unexpected consequences such as changes to the observed parachute failure modes. Additionally, the support hardware will also need to grow and neither the parachute nor the ancillary hardware will scale in a linear fashion.

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