Optimization of Earth Flight Test Trajectories to Qualify Parachutes for Use on Mars

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INTRODUCTION

Flight tests on Earth must closely match the anticipated operating conditions on Mars. Differences in atmospheric density, composition, speed of sound, and acceleration due to gravity make this difficult. Modeling and simulation can be used to develop optimal trajectories that best match the operating conditions on Mars.

MODELING & SIMULATION

Trajectories were simulated using a 2-DOF model in which two parachute opening loads/force models were implemented. Greene's method[1] was used to determine parachute inflation time.

Inflation curve model $$F_p = qC_{D,0}S_0C_x\left(\frac{t-t_{SI}}{t_{FI}-t_{SI}}\right)^n + m_p g\sin\gamma$$

Apparent mass model[2] $$F_p = qC_DS + \frac{d}{dt}\left[\left(m_a+m_p\right)V\right] + m_p g\sin\gamma$$

C_DS	Parachute drag area
$C_{D,0}$	Parachute steady-state drag coefficient
C_x	Inflation curve opening load factor
F_p	Parachute force
S_0	Nominal parachute area
V	Parachute velocity
g	Local acceleration due to gravity
m_a	Apparent mass
m_p	Parachute mass
n	Inflation curve exponent
q	Dynamic pressure
t	Time
t_{FI}	Time at parachute full inflation
t_{SI}	Time at start of parachute inflation (assumed to be at line stretch)
γ	Flight path angle (positive above the horizon)

CALIBRATION & VALIDATION

Data from the Viking parachute qualification flight test program (BLDT AV-4)[3] was used to calibrate the models and validate the simulation.

DESIGN OF OPTIMIZED EARTH FLIGHT TESTS

The design variables for the Earth flight test optimization were:

m_v :: the test vehicle mass.

h_0 :: the altitude at line stretch.

γ_0 :: the flight path angle at line stretch.

REFERENCE MARS TRAJECTORIES

A reference Mars trajectory was defined and optimized Earth flight test conditions were sought that best matched the following key quantities:

$F_{p,max}$ :: the peak opening load.

$t_{M=1.5}$ :: the time from full inflation to Mach 1.5. Disk-gap-band parachutes exhibit large cyclic loads above Mach 1.5.

$F_{p,avg}$ :: the average parachute load from full inflation to $t_{M=1.5}$, which is representative of the parachute's load time history.

Table. 1. Reference Mars parameters obtained using both force models.

	Inflation Curve	Apparent Mass
m_v (kg)	4,000	4,000
h_0 (km)	7.1	7.1
γ_0 (deg)	-30	-30
$F_{p,max}$ (kN)	639.1	641.3
$t_{M=1.5}$ (s)	3.22	3.43
$F_{p,avg}$ (kN)	321.6	312.6

RESULTS & CONCLUSIONS

Results for a point-design optimization of Earth flight test conditions using the two force models are shown in Table 2 and Figure 1.

- For a given force model, a good (within ±10% of the reference) match in the key responses can be obtained between the reference Mars trajectory and its corresponding Earth flight test.

- There are multiple combinations of m_v, h_0, and γ_0 that will yield acceptable Earth flight test designs.

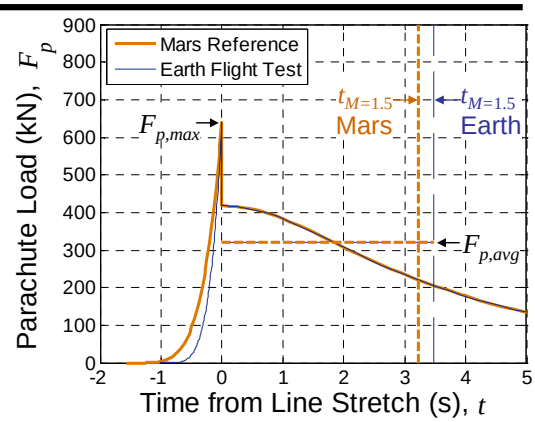

Fig. 1. Good agreement between Earth and Mars parachute force profiles using the inflation curve model.

Table 2. The two force models generate different optimal design variables* but similar responses.

	Inflation Curve	Apparent Mass
m_v (kg)	2,908	2,424
h_0 (km)	39.1	40.2
γ_0 (deg)	1.62	-45.3
$F_{p,max}$ (kN)	639.1	641.3
$t_{M=1.5}$ (s)	3.47	3.13
$F_{p,avg}$ (kN)	321.6	309.9

*Due to a shallow optimal surface with respect to the design variables m_v and γ_0.

Table 3. Differences between the two models are not large when the design variables are transposed.

	Inflation Curve	Apparent Mass
m_v (kg)	2,424	2,908
h_0 (km)	40.2	39.1
γ_0 (deg)	-45.3	1.62
$F_{p,max}$ (kN)	601.5	683.6
$t_{M=1.5}$ (s)	2.95	3.66
$F_{p,avg}$ (kN)	328.1	304.2

Valid parachute structural qualification tests that accurately simulate flight operations on Mars can be conducted in the Earth's atmosphere.

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