

Aerodynamics Database for Aerocapture of a Conceptual Morphable Entry System at Mars

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An aerodynamics database for aerocapture of a conceptual morphable entry system at Mars was developed. The vehicle is envisioned to employ deflections of its geometry to modulate angle of attack and sideslip angle for trajectory control. Modified Newtonian methods were used to compute hypersonic continuum aerodynamics. Direct simulation Monte Carlo calculations were carried out to compute data in the rarefied transitional regime. Free-molecular theory was used to compute values in the free-molecular regime. A bridging function method was then used to bridge data from all three flow regimes together and produce a database that can be used for future trajectory simulations to assess the vehicle's performance. The vehicle was found to have the control authority in hypersonic continuum to effect an 18 deg change in the trim angle of attack using a 10 deg deflection of the pitching control surfaces. Similarly, a 6 deg change in the trim sideslip angle could be achieved with a 5 deg deflection of the yawing control surfaces. Different configurations of the vehicle were found to be statically stable in pitch and yaw in the continuum regime, but unstable in the rarefied and free-molecular regimes.

Nomenclature

C_A	=	axial force coefficient
C_l	=	roll moment coefficient
C_m	=	pitch moment coefficient
C_N	=	normal force coefficient
C_n	=	yaw moment coefficient
C_Y	=	body side force coefficient
D	=	maximum diameter, m
F_{num}	=	ratio of real particles to simulated particles in DSMC
Kn	=	Knudsen number
L/D	=	lift-to-drag ratio
Ma	=	Mach number
P_b	=	bridging function
q_∞	=	freestream dynamic pressure, Pa
r_n	=	nose radius, m
T_∞	=	freestream temperature, K
V_∞	=	freestream velocity, m/s
α	=	angle of attack, deg
β	=	sideslip angle, deg
δ	=	deflection angle, deg
ρ_∞	=	freestream density, $\text{kg} \cdot \text{m}^{-3}$
σ	=	bank angle, deg

I. Introduction

DEPLOYABLE entry vehicles (DEVs) are unconventional aeroshells that can be stowed during launch and then later deployed before atmospheric entry to act as an aerodynamic decelerator. DEVs have the potential benefit of delivering the same mass payload as an equivalent rigid aeroshell, but with a stowed diameter that is 3–4 times smaller [1]. The most recognizable DEVs in recent literature are inflatable devices such as inflatable aerodynamic decelerators (IADs) [2–4] and mechanical deployables such as the adaptive deployable entry and placement technology (ADEPT) concepts [5–8]. These DEVs are visualized in Fig. 1.

Aside from its use as a decelerator, a DEV could potentially leverage configuration changes to perform direct force control (DFC) during guided atmospheric flight. DFC is a flight control method that independently modulates the angle of attack α and sideslip angle β of the vehicle to achieve a desired flight path both longitudinally and laterally. DFC has been investigated in studies for entry, descent, and landing [9] and for aerocapture applications [10]. It has been shown to provide propellant savings and improved landing and orbit insertion accuracy over traditional entry flight control approaches such as bank angle modulation. The benefits of DFC have encouraged further studies to look at potential means of achieving it. For example, an inflatable DEV was suggested for DFC in a study of a low L/D IAD using a morphing outer-mold-line during direct entry at Mars [11]. The Pterodactyl project also studied the use of mechanically actuated flaps for downrange and crossrange control to perform precision landing at Earth [12].

The present work introduces a conceptual mechanical DEV called the morphable entry system (MES), which uses deflections of its geometry to achieve DFC. The MES is intended for small satellite (smallsat) aerocapture at Mars in anticipation of potential smallsat missions there. Aerocapture is an aeroassist maneuver that uses a single pass through the atmosphere of a planet to reduce its orbital energy and capture into a desired orbit [13]. The significant ΔV required for orbit insertion at Mars (1–3 km/s for a low circular orbit) may be challenging for modern smallsat propulsion systems to wholly achieve on short time scales [14]. This situation can be alleviated by employing aerocapture to lower the required total ΔV to a level within the capabilities of most smallsat propulsion systems. This also translates to a reduction in total propellant mass needed for

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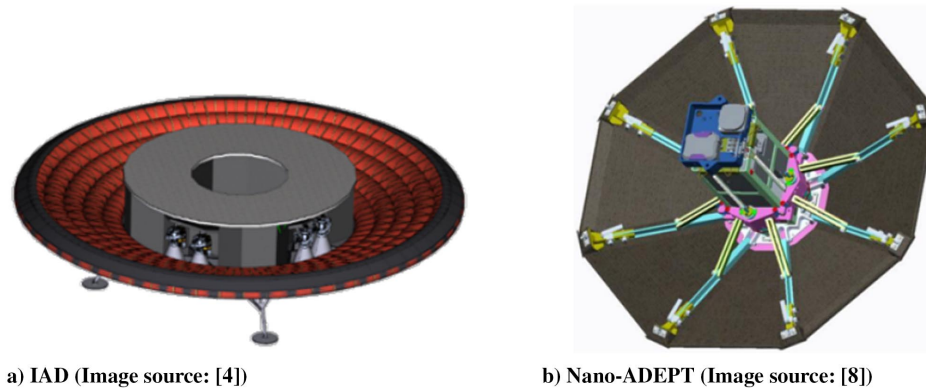


Fig. 1 The IAD and Nano-ADEPT deployable entry vehicle concepts.

orbit insertion, which is a known advantage of aerocapture compared to a fully propulsive approach [15]. Despite not being flight-proven yet, aerocapture has been shown to be a feasible orbit insertion technique at Mars for smallsats that can offer significant propellant mass fraction savings [16,17].

To assess how effective the shape-deflection strategy of the MES will be for achieving DFC during aerocapture, 6-degrees-of-freedom (DOF) trajectory simulations incorporating attitude dynamics are necessary. Such simulations in turn require an aerodynamics database for the MES in the Martian atmosphere. Trajectory analyses performed for Mars vehicles flying direct entries have employed aerodynamics databases, examples of which are described in Refs. [18–21]. Although it did not fly, the Aeroassist Flight Experiment vehicle was proposed for Mars aerocapture, and aerodynamics data were developed to compliment trajectory simulations, as described in Refs. [22,23]. Aerodynamics databases for DEVs such as ADEPT [24] and Pterodactyl [25] were also developed recently, albeit for an Earth atmosphere. The construction of these databases typically involved the following steps: First, an expected nominal trajectory for the vehicle is generated, from which several trajectory points are extracted for further analysis. At the selected trajectory points, detailed calculations of the vehicle's aerodynamics are performed via computational fluid dynamics (CFD). Analysis methods vary according to flow rarefaction, as discussed later in this paper. The results are then compiled into a database that can be queried based on the flight conditions (Mach number, dynamic pressure, and Knudsen number) and attitude (angle of attack and sideslip angle). Note that because the Pterodactyl vehicle uses control surfaces for trajectory control, its database can also be queried based on control surface deflections. The aerodynamics then become the inputs to a trajectory simulation tool. This traditional approach of database development was adopted with modifications for the present study. Because the present database was developed for an aerocapture vehicle, it does not contain data for supersonic, transonic, and subsonic flow conditions.

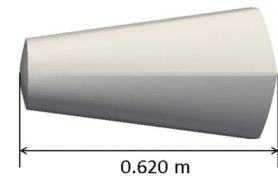
The objective of this paper is to describe the development of the aerodynamics database for the MES at Mars. This paper is organized as follows. Section II discusses the MES vehicle design. Section III presents the methods used to compute the aerodynamics at different flow regimes. Results are presented and discussed in Sec. IV, and Sec. V provides the Conclusions.

II. Morphable Entry System

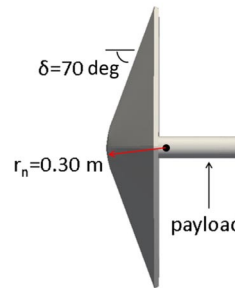
The MES is a DEV with a spherical segment nose cap and six panels, or “petals,” joined together by six ribs, as shown in Fig. 2. Inspired by ADEPT and the crocus flower, the MES geometry is a variation on the eight-paneled ADEPT design that was shown in Fig. 1b. The MES is envisioned to accomplish trajectory control by deflecting a subset of its petals to generate an asymmetric shape that induces aerodynamic pitching and yawing moments. This deflection strategy was inspired



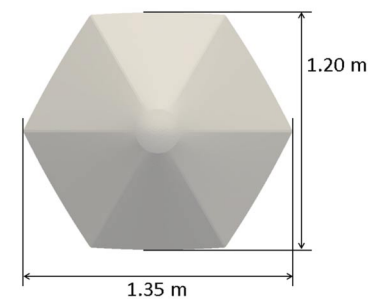
a) Image source : <https://www.flickr.com/photos/158350039@N03/26340253247> [accessed: 30 Oct. 2021]



b) Stowed configuration



c) Baseline vehicle side view



d) Baseline vehicle front view

Fig. 2 Notional configurations of the MES and the crocus flower inspiration.

by the crocus flower seen in Fig. 2a, which is a species that deploys and retracts its petals in response to sunlight.

A. Vehicle Definition

The vehicle dimensions are sized to be consistent with smallsat payloads because of the growing interest in the aerospace community to send smallsats to perform interplanetary science missions [26,27]. The stowed configuration in Fig. 2b would fit within the payload volume capabilities of an Evolved Expendable Launch Vehicle Secondary Payload Adapter ring, which can accommodate a $0.61 \text{ m} \times 0.71 \text{ m} \times 0.97 \text{ m}$ volume in each port [28]. For the fully deployed baseline vehicle configuration shown in Fig. 2c and 2d, all of the ribs and petals are oriented at 70 deg with respect to the local horizontal direction. This design decision is derived from the 70 deg sphere-cone geometry of past aeroshells sent to Mars, such as Pathfinder [29] and Mars Science Laboratory [30]. The ribs joining the petals are each 0.609 m in length. The maximum diameter D measured rib tip to rib tip is 1.35 m. Additionally, the ratio of the spherical nose radius to the maximum diameter is 0.22.

Notional examples of the pitching and yawing configurations of the MES are shown in Fig. 3. Petals are kept at their original 70° orientations when not used to control the vehicle. When a petal is deflected by the angle δ , the length from its tip to the nose cap integration point is assumed to be fixed. The petal's surface area will change as a result of the deflection, as seen in Fig. 4. This study assumed that a flexible thermal protection system (TPS) suited for DEVs [31–33] could accommodate the variable petal surface area and remain taut. Note that the aerodynamics of the various MES shapes is the focus of this paper, not the actuation method by which the deflected petals are achieved. TPS sizing and integration were also not considered. Therefore, the present study proceeds under the assumption that a mechanical deployment scheme and a suitable TPS are both available or could be designed and sized to achieve the subsequent shapes analyzed.

B. Pitching and Yawing Strategies

The definitions for angle of attack α , sideslip angle β , and bank angle σ are shown in Fig. 5 along with the body force and moment conventions. The petal and rib numbering systems are illustrated in Fig. 3a. To change the aerodynamics of the vehicle for trajectory control, a set of ribs is actuated to form an asymmetric shape. For example, ribs 1 and 6 can be actuated to deflect petals 1, 2, and 6 away from the flow, as seen in Fig. 4. This strategy would create a negative pitching moment $-C_m$ that would tend to modulate α negatively. The opposite strategy of actuating ribs 3 and 4 to deflect petals 3, 4, and 5 would generate a positive pitching moment $+C_m$ that modulates α positively. Similarly, yawing motion is achieved by deflecting panels 2, 3, 5, and 6 away from the flow. Actuating rib 2 to deflect petals 2 and 3 simultaneously causes a negative yaw moment $-C_n$, whereas actuating rib 5 to deflect petals 5 and 6 induces a positive yaw moment $+C_n$. Although not the focus of this work, roll moments C_l can be achieved through the use of reaction control system thrusters or by leveraging yaw-to-roll strategies [12]. This work did not consider “diagonal-only” deflections (e.g., actuating ribs 1 and 2 to deflect petals 1–3 away from the flow).

III. Computational Methods

To supply the relevant flow conditions for this study, an aerocapture trajectory at Mars targeting a circular parking orbit with a 400 km altitude and 30 deg inclination was generated via 3-DOF simulation [17]. These simulations used the Mars Global Reference Atmosphere Model (2010) to model the Martian atmosphere [34]. The nominal trajectory and the expected range-of-flight Knudsen numbers Kn are shown in Fig. 6. All Kn values were computed as the ratio of the mean free path, derived from the variable soft sphere (VSS) model, to the maximum diameter D of the MES. As shown in Fig. 6b, the vehicle transitions among free-molecular, rarefied transitional, and continuum flow regimes. Therefore, a single-point bridging function method [35] was used to bridge the aerodynamic coefficients from these regimes together. The red circular markers in Fig. 6a correspond to the analysis points in Table 1, which were used in the bridging

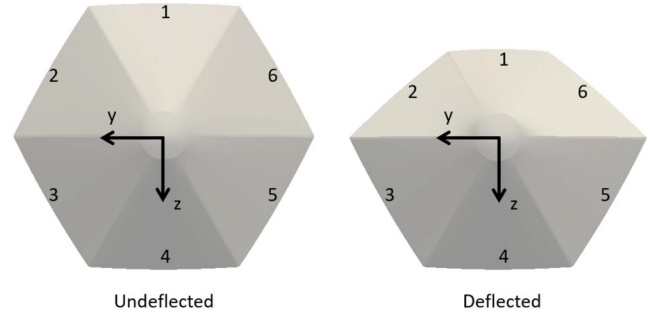


Fig. 4 Deflecting petal 1 changes its surface area as well as those of petals 2 and 6.

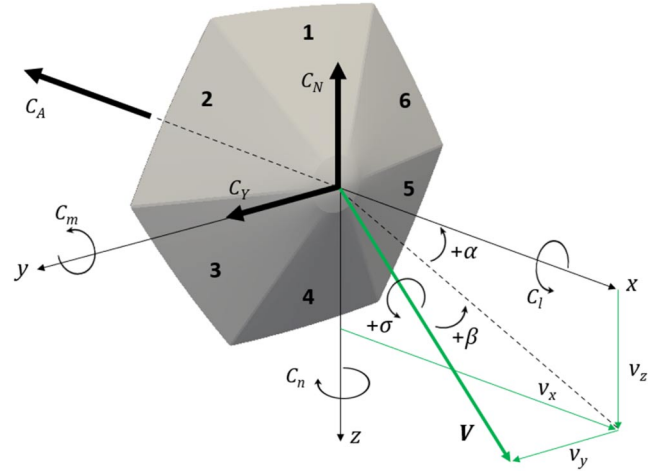


Fig. 5 Definition of wind frame angles and the body force and moment coefficients.

method. The aerodynamics database was constructed such that the aerodynamic coefficients could be queried based on freestream Kn or dynamic pressure q_∞ , as well as α , β , and δ .

Bridging relations for rarefied transitional flow have been used to develop aerodynamics databases for such vehicles as the Stardust capsule [36]. Bridged aerodynamics data agreed well with direct simulation Monte Carlo (DSMC) data for the Stardust vehicle, which demonstrates the reliability of bridging relations in generating aerodynamics data for a wide range of flow conditions. Bridging relations can also reduce the overall computational cost, which was the primary reason for its use in this effort. Because aerodynamics data is needed not only for multiple flight velocities and attitudes, but also for multiple vehicle configurations, a reduction in computational effort was desired. The following sections describe the bridging method and computational tools in more detail.

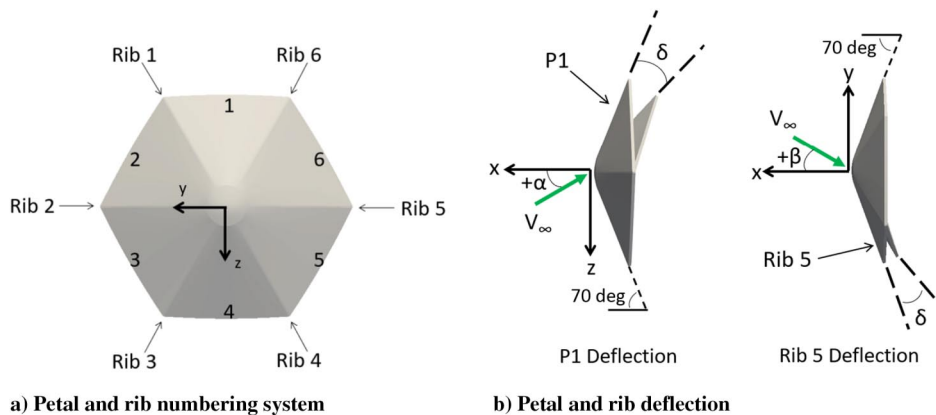


Fig. 3 The petal and rib numbering system and deflection strategies are shown.

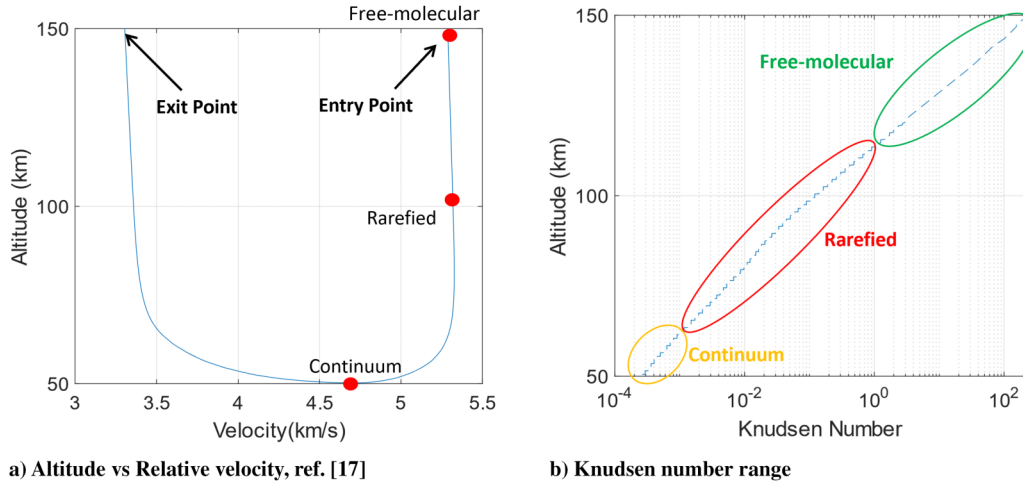


Fig. 6 Nominal MES aerocapture trajectory and the expected flight Knudsen numbers.

Table 1 Flow conditions used in the single-point bridging method

Alt, km	V_∞ , km/s	ρ_∞ , kg/m ³	T_∞ , K	Kn_∞	Ma_∞	q_∞ , Pa	Analysis tool(s)
150.0	5.2869	1.756e-10	290.72	232.24	19.56	2.45e-03	Free-molecular panel code
106.7	5.3138	8.882e-08	140.98	0.3364	28.23	1.25	SPARTA DSMC
50.5	4.8350	1.186e-04	155.36	2.63e-04	24.47	1386.38	Modified Newtonian panel code

A. Single-Point Bridging Method

A bridging method was chosen to reduce the cost of computing rarefied transitional aerodynamic coefficients. The single-point bridging relation method of Wilmoth et al. [35] was adopted for this purpose. The bridging relation equation gives an estimate of an aerodynamic coefficient at some intermediate rarefied transitional condition from its known continuum and free-molecular values. The bridging function provides a factor used to scale the continuum and free-molecular coefficients in the bridging relation. The error function-logarithmic (*erf-log*) bridging function of Ref. [37] was used in the bridging relation for this work. As implied by its name, the single-point bridging relation method only requires DSMC data for a single transitional flow condition located between the continuum and free-molecular limits of the nominal trajectory. Figure 7 illustrates the use of three known aerodynamic coefficients at different Kn values to construct the bridged aerodynamics data, shown as the solid line.

Each aerodynamic coefficient C has a bridging relation of the form

$$C = P_b C_{fm} + (1 - P_b) C_{co} \quad (1)$$

where the error function-logarithmic (*erf-log*) bridging function P_b is given by

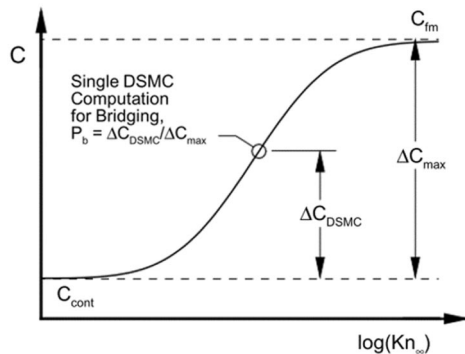


Fig. 7 The erf-log single-point method visualized (Image source: [34]).

$$P_b = \frac{1}{2} \left(1 + \operatorname{erf} \left\{ \frac{\sqrt{\pi}}{\Delta Kn} \log \left[\frac{Kn_\infty}{Kn_m} \right] \right\} \right) \quad (2)$$

and C_{fm} and C_{co} are the known free-molecular and continuum values of the coefficient, respectively. In Eq. (2), ΔKn is the logarithmic width of the transitional regime and Kn_m is the midpoint of the transitional regime where $P_b = 1/2$. To illustrate the bridging process, suppose that the free-molecular, rarefied transitional, and continuum values for the axial force coefficient ($C_{A,fm}$, $C_{A,tr}$, and $C_{A,co}$, respectively) at $\alpha = 0$ deg and $\beta = 0$ deg are known. First, $C_{A,tr}$ is inserted into the left-hand side of Eq. (1), whereas $C_{A,fm}$ and $C_{A,co}$ are inserted into the right-hand side. Solving for P_b at the current transitional condition gives

$$P_{b,tr} = \frac{C_{A,tr} - C_{A,co}}{C_{A,fm} - C_{A,co}} \quad (3)$$

$P_{b,tr}$ is then substituted back into Eq. (2) to solve for Kn_m . This provides,

$$Kn_m = \frac{Kn_{tr}}{\exp((\Delta Kn / \sqrt{\pi}) \operatorname{erf}^{-1}(2P_{b,tr} - 1))} \quad (4)$$

With Kn_m known, the intermediate *erf-log* function value P_b at any intermediate Kn_∞ can be obtained from Eq. (2). Lastly, this intermediate P_b is substituted back into Eq. (1) to obtain the C_A value at Kn_∞ within the ΔKn range. The same procedure applies when calculating the other aerodynamic force coefficients C_Y , C_N and moment coefficients C_l , C_m , C_n . The resulting coefficients are functions of Kn that vary for different α and β combinations. In this work, the logarithmic width was defined as $\Delta Kn = \log(Kn_{fm} - Kn_{co})$.[§] From the nominal trajectory, the resulting logarithmic width is $\Delta Kn = \log(232.24 - 0.000263) = 5.448$. Application of Eqs. (1–4) thus provides the bridging relation for any aerodynamic coefficient needed.

[§]Reference [34] defined the universal transitional width as $\Delta Kn = \log(500) = 6.2146$, which was based on existing DSMC data for different vehicles, such as Viking, Pathfinder, and Stardust.

B. Regime-Specific Tools

In the free-molecular regime, analytic expressions for pressure and shear stress [38] were adapted into a panel code to compute the corresponding aerodynamic coefficients. The code takes as input a triangulated surface and computes pressure and shear stress on each surface element. The aerodynamic coefficients are obtained by integrating the pressures and shear stresses over the entire surface geometry. Flow shadowing occurs when the angle between the unit outward normal of a surface element $\hat{n}$ and the flow velocity unit direction $\hat{V}_\infty$ is less than 90 deg (i.e., $\hat{V}_\infty \cdot \hat{n} > 0$). The pressure and shear stress on shadowed elements are negligible and are set to zero in the panel code. Surface-particle interactions were assumed to be fully diffuse (i.e., the rebound velocities of a particle before and after colliding with the surface are not equal). Full thermal accommodation was also assumed so that the reflected temperature of particles is equal to the wall temperature. The wall temperature was estimated through the Stefan-Boltzmann law for all flow conditions studied. Because the Martian atmosphere is predominantly CO_2 , the specific gas constant for free-molecular computations was assumed to be $188.9 \text{ J/kg} \cdot \text{K}$ and the ratio of specific heats was set to $\gamma = 1.33$ [39]. The first row of Table 1 provides the relevant flow conditions used in the free-molecular panel code.

For hypersonic continuum calculations, the modified Newtonian theory for pressure was also adapted into a panel code. The code also takes as input a triangulated surface and computes the pressure on each surface element. The aerodynamic forces are obtained by integrating the pressures over the entire surface. Flow shadowing was handled in the same manner as in the free-molecular code. The code also assumed that $\gamma = 1.33$ for the gas flow. Because blunt body hypersonic flows are pressure dominated, an inviscid assumption was deemed acceptable for the present study. The third row of Table 1 provides the relevant flow conditions used in the continuum panel code.

The Stochastic Parallel Rarefied-Gas Time-Accurate Analyzer (SPARTA) [40][†] open-source DSMC solver was used to compute the rarefied transitional aerodynamics. The second row of Table 1 provides the relevant flow conditions. A flow mixture of 97% CO_2 and 3% N_2 was assumed in all DSMC calculations. Both rotational and vibrational energy modes of CO_2 were accounted for. The variable soft sphere (VSS) model was chosen to model particle collisions [38]. The DSMC run parameters are shown in Table 2. The computational domain was a $1.6 \text{ m} \times 2.0 \text{ m} \times 2.0 \text{ m}$ box that fully enclosed the MES surface mesh. The two-level Cartesian cell hierarchy displayed in Fig. 8 contains 58,212 cell volumes. Cell refinement was based on the requirement that cell dimensions are approximately one-third (1/3) of the mean free path. Each computational cell contained 20 simulated particles to ensure sufficient collisions were being modeled and sampled. This decision was reached after an extra DSMC calculation using 40 simulated particles revealed a small change in the aerodynamics, as shown in Table 3. The unstructured surface meshes for different configurations of the vehicle contained approximately 83,000 elements. A finer surface mesh of approximately 330,000 elements was used in a surface mesh refinement study, which indicated a negligible change in the aerodynamic coefficients, as shown in Table 4. Therefore, the coarser surface mesh was deemed sufficient. The surface meshes used in the DSMC calculations were also used in the free-molecular and continuum panel code calculations. Each DSMC simulation was considered converged if the change in the aerodynamic body forces was less than 1% over 50,000 consecutive time steps. All simulations converged after 100,000 total time steps.

C. Chemistry Modeling

Collisions between particles can potentially result in chemical reactions. A brief study was conducted to determine the influence of a chemically reacting flow for modest Knudsen numbers ($0.01 < Kn < 1$) on the aerodynamic coefficients. The chemical reactions modeled were adapted from Ref. [41] and included 40

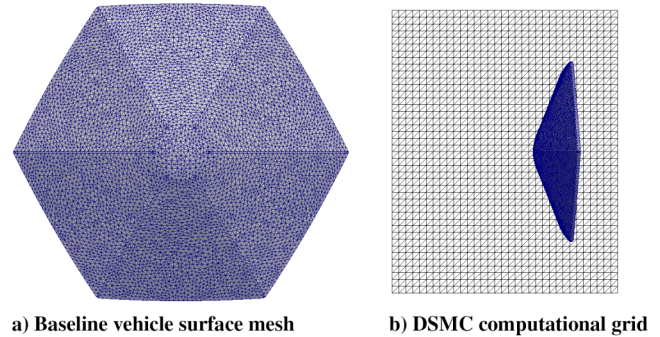


Fig. 8 An example visualization of the surface mesh and computational grids used in all DSMC calculations.

Table 2 DSMC simulation parameters

Parameter	Value
Knudsen number	0.3364
Number density (m^{-3})	$1.21\text{e}18$
Simulated particles	$1.16\text{e}06$
$F_{\text{num}} = \frac{\text{Real particles}}{\text{Simulated particles}}$	$6.68\text{e}12$
CO_2 mass fraction	0.97
N_2 mass fraction	0.03
Time-step size (s)	$1.74\text{e}-06$
Total time-steps	100,000

Table 3 Results of particle count convergence study for the baseline vehicle ($Kn = 0.05$, $\alpha = -15 \text{ deg}$, $\beta = 0 \text{ deg}$)

Particle count (per cell)	C_A	C_N	C_m
20	1.55005	-0.22116	-0.00609
40	1.55029	-0.22124	-0.00612

Table 4 Results of surface mesh refinement study for petal 1 deflected at $\delta = 30 \text{ deg}$ ($Kn = 0.34$, $\alpha = 0 \text{ deg}$, $\beta = 0 \text{ deg}$)

Element count	C_A	C_m
83,000	1.464576	-0.099200
328,000	1.464543	-0.099205

dissociation reactions and 14 exchange reactions involving CO_2 , CO , C , N_2 , N , NO , O_2 , and O . The study indicated that accounting for chemical reactions did not significantly alter the aerodynamic coefficients of the vehicle in the rarefied transitional regime. For instance, the surface pressure contours are very similar regardless of chemical reactions in the flow, as shown in Fig. 9. The low sensitivity of the rarefied transitional aerodynamics to chemical reactions is further supported by Table 5, which indicates a small difference in C_A of the baseline vehicle as a result of simulating chemical reactions. As the flow increases in rarefaction and collision frequency decreases, the effects of chemistry are expected to be negligible. Therefore, all DSMC simulations in this work did not simulate chemical reactions.

By using the modified Newtonian approach in the continuum regime, chemistry effects were not directly modeled. To gauge the impact of doing so, a limited set of higher fidelity calculations for the baseline configuration were carried out using the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) Navier-Stokes flow solver [42] at the continuum flow condition, shown in Table 1. Non-equilibrium chemistry was modeled using a two-temperature gas model with eight species (CO_2 , CO , C , N_2 , N , NO , O_2 , and O). The freestream composition was modeled as 97% CO_2 and 3% N_2 by mass. The

[†]The SPARTA software is available on <http://sparta.sandia.gov> [accessed 8 June 2020].

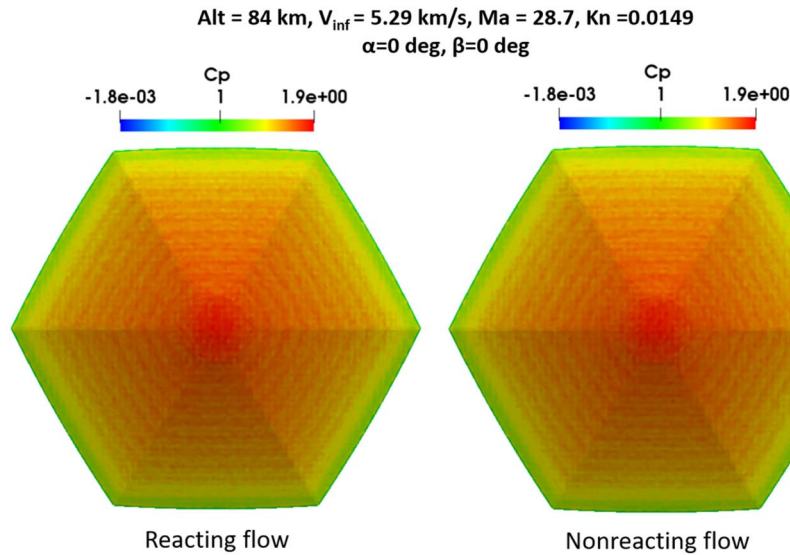


Fig. 9 DSMC comparison of chemistry effects on surface pressure distribution.

Table 5 Effect of chemical reactions on the aerodynamics at two rarefied flow conditions

Altitude, km	Kn	α , deg	β , deg	C_A (reactions)	C_A (no reactions)
94	0.0519	0	0	1.6412	1.6411
84	0.0149	0	0	1.5478	1.5477

LAURA results for lift-to-drag ratio L/D and C_m are presented in Fig. 10 (open symbols). The nonreacting, modified Newtonian results are included for comparison (solid lines).

Because the lift and drag are greatly influenced by the pressure distribution on the body, the modified Newtonian and LAURA results for L/D agree well, as shown in Fig. 10a. Although the C_m trends are similar in Fig. 10b, the modified Newtonian results for C_m are greater in magnitude than those predicted by LAURA at nonzero α . The maximum absolute difference is 0.00967, which occurs at $\alpha = -15 \text{ deg}$. The maximum viscous shearing was found near the shoulder of the vehicle and was only about 5% of the local surface pressure ($\alpha = -15 \text{ deg}$ case). Based on this, it can be inferred that gas chemistry has the greater influence on the difference in C_m , rather than viscous effects. An example of this influence is that of reactions in the shock layer shifting the sonic line location on the aeroshell surface, which can influence the resulting pitching moment, as described by Gnoffo et al. [43].

These results indicate that modeling gas chemistry in the continuum regime is important for computing the moment coefficients. However, this comes at the cost of additional computational effort. Limited computational resources necessitated a balance between accuracy and computational effort. As noted earlier, the modified Newtonian approach can reasonably capture hypersonic continuum

aerodynamics for blunt bodies because it is pressure-dominated. Therefore, the modified Newtonian approach was deemed acceptable for the present study, although the reduction in the accuracy of the moment coefficients by neglecting chemistry is acknowledged. The use of correction factors to account for the effects of reacting gas on the moment coefficients is suggested.

D. Run Matrix

The tools discussed in the preceding section were used to build the aerodynamics database of the MES. The three flow conditions required for the single-point bridging method are shown in Table 1. The first row of Table 1 is at the atmospheric interface where the flow conditions are free molecular. The corresponding panel code was used to compute the aerodynamic coefficients of the MES at this altitude. The middle row of the table shows the flow conditions at the rarefied transitional analysis point where DSMC is appropriate. The last row gives the continuum conditions where the modified Newtonian panel code was used. At each analysis point, the deflected configurations of the MES were evaluated according to the run matrix in Table 6. For the pitching configuration shown in Fig. 3b, the petal deflection angles assumed for petal 1 (P1) were $\delta = \{0, 10, 20 \text{ deg}\}$.

Table 6 The angle of attack, sideslip angle, and petal deflections evaluated to develop the aerodynamics database

Flow condition	Alt, km	α , deg	β , deg	P1 δ , deg	R5 δ , deg
Free molecular	150.0	$\{-30:5:30\}$	$\{0, 5, 10\}$	$\{0, 10, 20\}$	$\{0, 5, 10\}$
Rarefied	106.7	$\{-30:5:30\}$	$\{0, 5, 10\}$	$\{0, 10, 20\}$	$\{0, 5, 10\}$
Continuum	50.5	$\{-30:5:30\}$	$\{0, 5, 10\}$	$\{0, 10, 20\}$	$\{0, 5, 10\}$

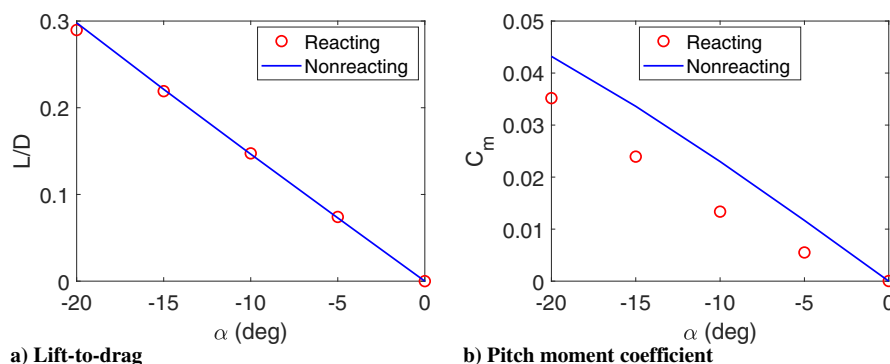


Fig. 10 A comparison of continuum aerodynamics with and without chemistry effects.

As for the yawing configurations in Fig. 3b, the deflection angles assumed for rib 5 (R5) were $\delta = \{0, 5, 10\}$ deg. Note that $\delta = 0$ deg is simply the undeflected baseline vehicle shape seen in Fig. 4.

IV. Results and Discussion

The static aerodynamic coefficients of the MES at the various configurations were computed with the single-point, erf-log bridging method. The results were compiled into a database, which can be queried based on Kn or q_∞ , as well as α , β , and δ . The database will be used in future studies of the vehicle's direct force control performance. This section presents data extracted from the database to discuss notable aerodynamic characteristics of the MES.

A. Static Aerodynamics

The static aerodynamics of the MES are presented in Figs. 11–13. Representative results from each of the three flow regimes are

included to show the effect of flow rarefaction. The L/D characteristics of the baseline vehicle (i.e., all $\delta = 0$ deg) are shown in Fig. 11. In all three flow regimes, the MES produces positive lift at negative angles of attack. This is consistent with other blunt-body aeroshells that have flown on Mars. The L/D is also largest in the continuum regime due to the greater atmospheric density. Because drag increases with rarefaction, L/D decreases as the flow approaches free-molecular conditions.

The pitching characteristics of the MES are shown in Fig. 12. All moment coefficients were computed relative to the assumed nominal center of gravity (c.g.) location of $0.3D$ (0.405 m) aft of the nose. Knowing where in its trajectory the MES is stable and unstable in pitch is important for future trajectory simulations. Static stability in pitch is demonstrated when $\partial C_m / \partial \alpha < 0$, meaning that a restoring pitch moment exists for nonzero α . On the other hand, $\partial C_m / \partial \alpha > 0$ means that a destabilizing pitching moment exists for nonzero α . The MES must employ its petal deflection control to manage pitching

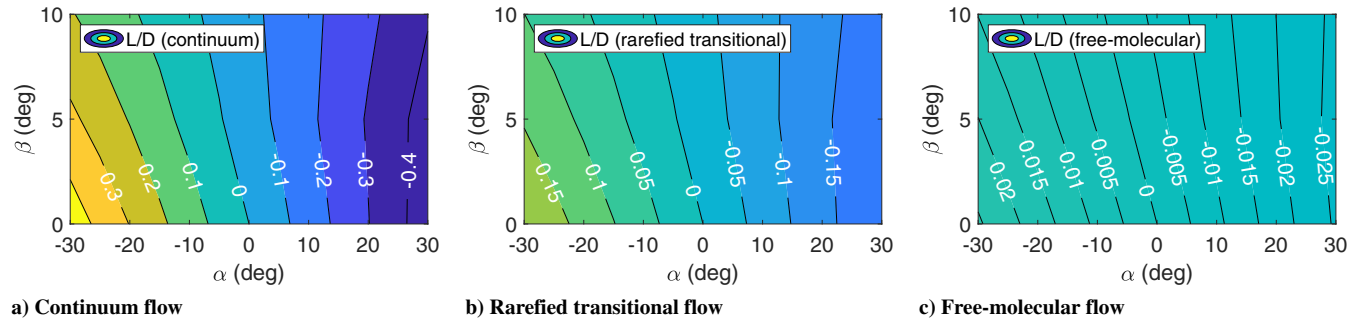


Fig. 11 Lift-to-drag characteristics of the MES baseline vehicle.

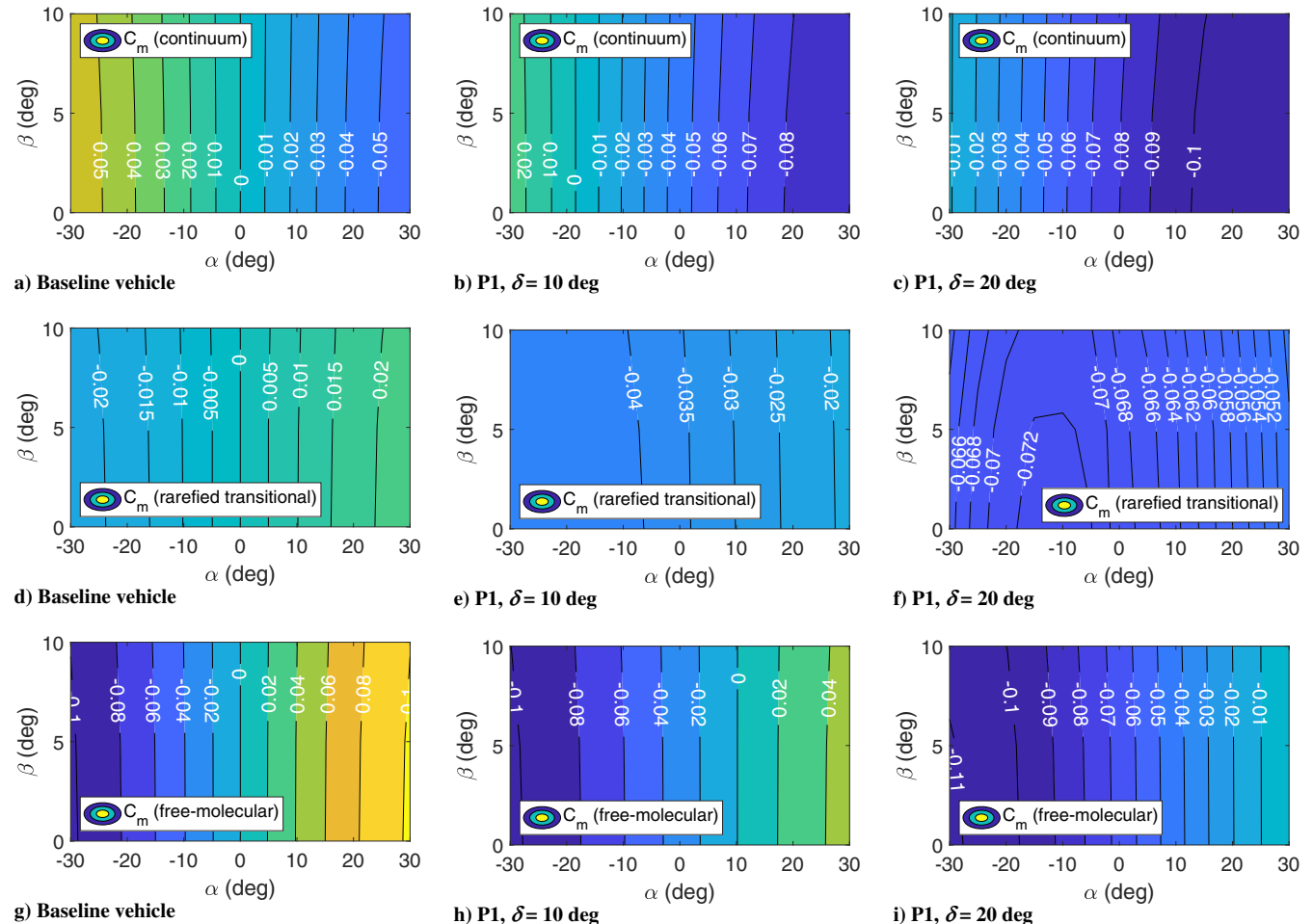


Fig. 12 Pitching characteristics of the MES.

instabilities. Figure 12a demonstrates that the baseline shape is statically stable in pitch in hypersonic continuum conditions. In the rarefied transitional and free-molecular conditions shown in Figs. 12d and 12g, the vehicle is statically unstable in pitch. Frictional forces at higher flow rarefaction cause this destabilizing motion, which has been observed in other blunt-body entry vehicles such as Mars Pathfinder [44]. The observed instability persists until $0.04 < Kn < 0.05$, which corresponds to an altitude of approximately 93 km and $q_\infty = 9.4$ Pa on the nominal trajectory. Below this altitude, $\partial C_m / \partial \alpha < 0$ and the baseline vehicle is always stable. The same pitch static stability trends can be observed for the deflected cases in Fig. 12. Note that β does not greatly affect C_m , except in rarefied transitional conditions where δ is significant (see Fig. 12f).

By deflecting petal 1 (P1) as shown in Fig. 3b, the MES can achieve a negative moment that decreases α for pitch-down control. Alternatively, pitch-up control is achieved by deflecting petal 4 (P4), which is the direct opposite of P1. Figure 12 shows C_m for the pitch-down configuration at $\delta = 10$ deg and $\delta = 20$ deg. Clearly, the pitch-down configuration is statically unstable at higher flow rarefaction in the present α and δ ranges. Again, β does not significantly affect C_m , but the flow rarefaction does. A new trim α can be achieved through nonzero δ , for example, $\alpha_{\text{trim}} = -18.5$ deg for $\delta = 10$ deg in the continuum condition shown in Fig. 12b. This implies that the envisioned petal deflections of the MES can be used to achieve a desired trim orientation. Intermediate δ values may be necessary to achieve some desired attitudes. Therefore, a cubic interpolation routine was also developed to complement the database and enable the querying of coefficients based on intermediate Kn and δ combinations.

Nonzero β values were simulated to obtain the yawing characteristics of the vehicle. Figure 13 shows the yawing coefficient C_n as a function of α and β at varying levels of rarefaction. In the continuum

regime, the baseline vehicle is stable in yaw because $\partial C_n / \partial \beta > 0$, meaning a restoring yaw moment exists for a nonzero β . The baseline vehicle is also statically unstable in yaw (as it is in pitch) for increasing levels of flow rarefaction because $\partial C_n / \partial \beta < 0$ at these conditions. The instability persists until $Kn \approx 0.04$. The baseline vehicle appears to trim in yaw at $\beta = 0$ deg and $\beta = -6.8$ deg at the rarefied transitional flow condition shown in Fig. 13d. This trim behavior warrants further investigation. Because no β control is anticipated in the rarefied portions of the MES trajectory, any complications due to dual β_{trim} values may be avoided.

The yawing strategy for the MES is to deflect rib 2 or rib 5 by δ . The yawing shape corresponding to rib 5 deflections (R5) was used in all computations, and representative results for C_n are also shown in Fig. 13. Deflecting R5 induces a positive moment about the body- z axis ($+C_n$), which corresponds to a “yaw-to-the-right” strategy to modulate β negatively. The results show that the R5 shape is capable of this in the continuum regime. At moderate α , the trim β shifts from 0 deg to approximately 6° via an R5 deflection of $\delta = 5$ deg, as shown in Fig. 13b. Figure 13 also indicates that the yawing configurations are statically stable in yaw in the continuum regime only. In the envisioned application of the MES, out-of-plane motion control will be limited to small changes in β . Therefore, the database includes data for an R5 deflection of up to 10° only. Note that α moderately impacts C_n for the R5 shapes especially in rarefied transitional conditions, as shown in Figs. 13e and 13f.

To further reduce the overall computational cost of this analysis, only the P1 and R5 configurations were used in all calculations. Deflecting petal 4 (P4) produces the same shape as when P1 is deflected, only it is rotated about the body- x axis by 180 deg. This symmetry is leveraged and the aerodynamic coefficients corresponding to the P4 shape are taken directly from the P1 shape’s computed values and assigned the appropriate algebraic sign. For example,

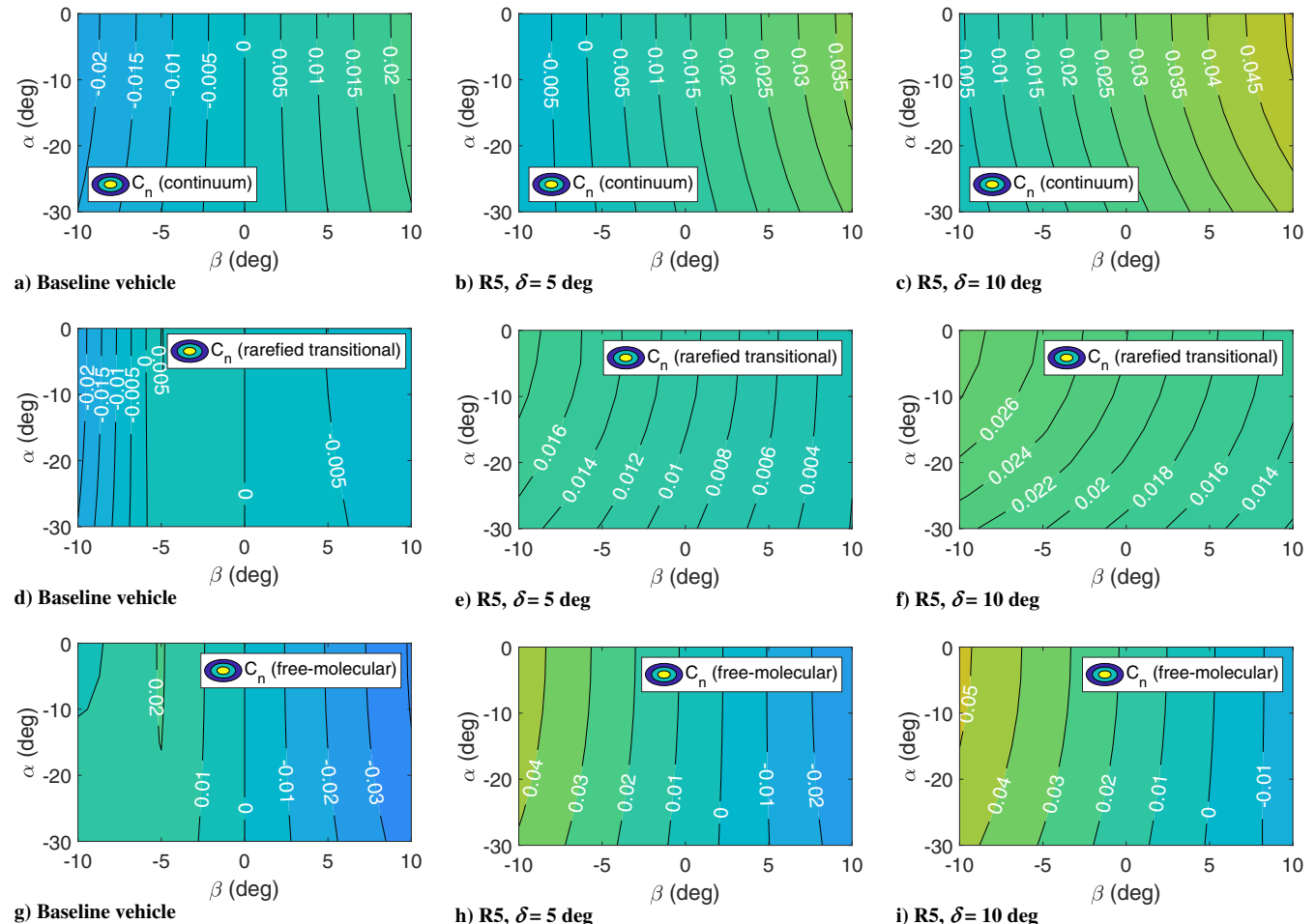


Fig. 13 Yawing characteristics of the MES.

$C_m = -0.056$ when deflecting P1 by $\delta = 10$ deg at $\alpha = 5$ deg, $\beta = 0$ deg in the continuum regime, as shown in Fig. 12b. Because P4 produces an equal but opposite pitch effect as P1, $C_m = 0.056$ for the P4 shape at the same δ and Kn combination for $\alpha = -5$ deg, $\beta = 0$ deg. The same symmetry argument applies to the yawing configurations of the MES.

The pitching and yawing effectiveness of the different configurations shown can also be extracted from the database. Computing the gradients of C_m and C_n with respect to δ yields the control authority measures $\partial C_m / \partial \delta$ and $\partial C_n / \partial \delta$. Figure 14 shows the pitching effectiveness of the P1 deflections ($\partial C_m / \partial \delta$) and the yawing effectiveness of R5 deflections ($\partial C_n / \partial \delta$) as functions of δ and Kn . From Fig. 14a, the magnitude of $\partial C_m / \partial \delta$ increases with smaller δ in the continuum limit. Conversely, $\partial C_m / \partial \delta$ increases in magnitude with δ in the free-molecular limit. This trend is preserved for all α and β combinations studied. Representative values of $\partial C_n / \partial \delta$ are also shown in Fig. 14b. As expected, the control authority of R5 deflections appears to increase with decreasing Kn . This trend is consistent regardless of the α and β combination. The nearly vertical contour lines for $\beta = 0$ deg in Fig. 14b indicate that $\partial C_n / \partial \delta$ is quasi-constant with δ in the continuum regime. This is not true however in the free-molecular limit, as $\partial C_n / \partial \delta$ always varies with δ . This quasi-constant behavior also disappears in the continuum regime at nonzero β . $\partial C_m / \partial \delta$ and $\partial C_n / \partial \delta$ will be essential to the development of a suitable flight controller for subsequent aerocapture trajectory simulations to evaluate the DFC capabilities of the MES.

B. Database Verification

Additional DSMC calculations were carried out to generate aerodynamics data for comparison with the database. Figure 15 shows C_m at $\alpha = -15$ deg, $\beta = 0$ deg for the baseline and P1-deflected MES configurations. The solid and dashed lines correspond to the C_m values of the P1-deflected and baseline configurations, respectively, for the entire Kn range of the database. The circle and square markers correspond to the C_m values for the P1-deflected and baseline configurations, respectively, that were obtained via DSMC. The maximum difference observed between the DSMC and database values in Fig. 15 is 0.00475. This maximum difference corresponds to the data point closest to the continuum limit ($Kn = 0.0507$), as indicated in Fig. 15. This suggests that the agreement between DSMC data and the database may degrade as Kn continues to decrease. Qualitatively, a good fit exists between the DSMC data and the database in the

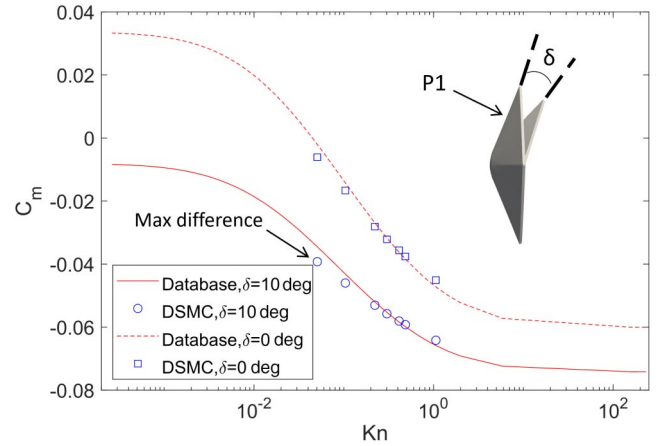


Fig. 15 A comparison of C_m from the database and DSMC calculations at $\alpha = -15$ deg, $\beta = 0$ deg.

rarefied transitional regime. This highlights the usefulness of the bridging method in generating rarefied transitional aerodynamics data, while reducing the number of expensive DSMC simulations.

As noted in Ref. [35], the accuracy of bridging methods is dependent upon the accuracy of the continuum and free-molecular construction points used to generate the bridging parameters. The engineering-level panel methods used to compute the aerodynamics at these Kn extremes led to a reduction in fidelity, as noted earlier. Using higher fidelity tools could improve the fit between the DSMC data and the bridged database. For example, additional Navier–Stokes solutions could be carried out to replace the modified Newtonian estimates used to build the database. Running additional DSMC with no collisions is also an alternative method of computing free-molecular aerodynamics for future refinements of the database. However, the increase in fidelity translates to increased computational cost. Presently, the study of applying the MES to direct force controlled aerocapture is at the proof-of-concept level. Therefore, the modified Newtonian and free-molecular methods described were determined to be sufficient. The current database is an acceptable initial estimate of the vehicle's aerodynamic characteristics that enables the study of its flight performance in subsequent trajectory simulations.

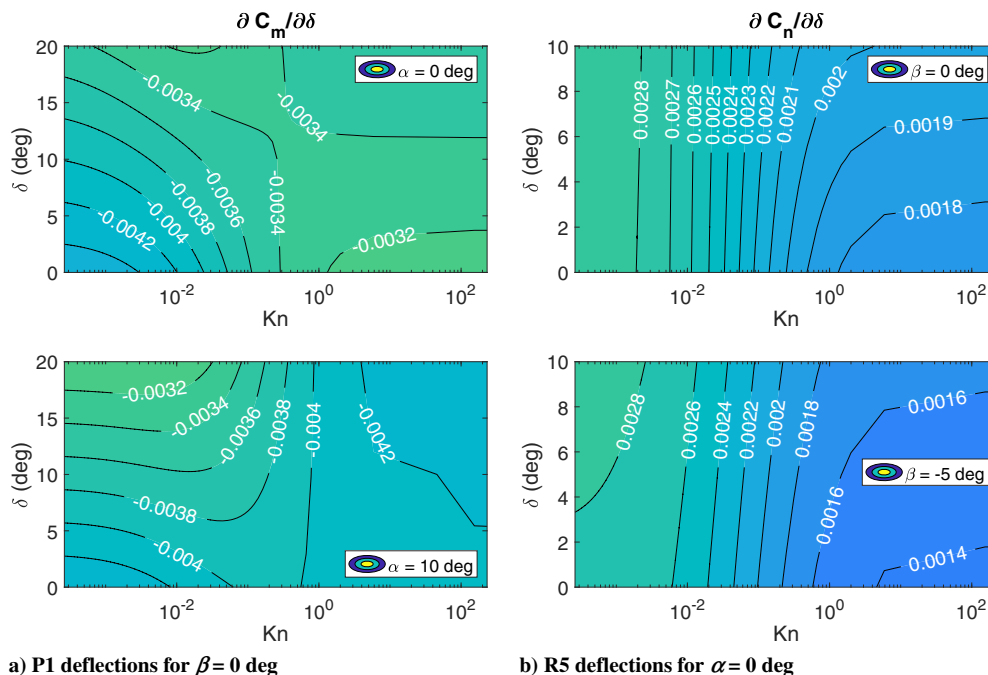


Fig. 14 The pitching effectiveness of P1 deflections and yawing effectiveness of R5 deflections.

V. Conclusions

The development of an aerodynamics database for aerocapture of the MES at Mars was presented. The database contains the aerodynamic coefficients of the various configurations of the MES at several α and β values for a wide range of Kn conditions in the Martian atmosphere. Key findings include the following: 1) the MES configurations studied are statically unstable in pitch and yaw in the rarefied and free-molecular regimes, but stable in the continuum regime, 2) the control authority of the pitching configurations is stronger at smaller δ deflections in the continuum regime, 3) the control authority of the yawing configurations is nearly constant with δ for zero β , but not for nonzero β in the continuum regime, and 4) the single-point erf-log function bridging method was found to be useful for generating a large set of aerodynamics data, while reducing the number of expensive DSMC calculations. A limited set of higher fidelity data generated via Navier–Stokes CFD revealed that the aerodynamic moments are significantly influenced by gas chemistry in the continuum regime. The present database will be used in future trajectory simulations to assess the feasibility of the petal deflection strategy of the MES to achieve direct force controlled aerocapture at Mars.

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