3D Aerodynamic Analysis – **Dr. Felix Finger**

To assess the aerodynamic performance, the Dash-1 version of the RMMP was analyzed using steady-state RANS simulations. The aircraft was analyzed for two flow conditions: 2° angle of attack (AoA) at MSL and 2° AoA at 150,000 ft, which is representative of the flow conditions on Mars. At this early design stage, no attempt was made to precisely model Mars' atmosphere in CFD. The simulation at MSL conditions (high Reynold's number) was performed as a reality check, against which the RDSwin drag numbers could be compared. The simulation parameters for both flow conditions are shown in Table XXX.

Table XX – 3D RANS simulation parameters.

Parameter	MSL	105k ft
Free stream velocity V_∞ [m/s]	66	77.17
Reference pressure p_∞ [Pa]	101.325	867.5
Density ρ_∞ [kg/m3]	1.225	0.01322
Dynamic viscosity μ [Pa·s]	$1.812 \cdot 10^{-5}$	$1.4869 \cdot 10^{-5}$
Reynold's number Re [-]	$9.593 \cdot 10^{6}$	$0.142 \cdot 10^{6}$
Turbulence intensity (inlet) [-]	1%	1%
Turbulent viscosity ratio (inlet) [-]	10	10

The simulation was set up according to the recommendations outlined in Ref. [1]. The RANS equations were solved using the assumptions of incompressible flow, and the SST k-ω (Menter) turbulence model was used. The bullet-shaped flow field was divided into finite volumes using an unstructured cartesian cut cell mesher with a dedicated prism mesh, which discretizes the boundary layer. Boundary layer thickness for each aircraft part and both flow conditions was determined, ensuring y^+ values below 1 on all aircraft's surfaces. The surface mesh size was adjusted to give approximately 70 cells over the wing in chordwise direction. To decrease the computational effort, a half-model was used, and a symmetry condition was applied. To reduce the cell count, the landing gear was excluded from the model. These measures resulted in a domain size of 21 Mio cells, which represented the maximum possible cell count on the available workstation. Due to this memory limitation, a mesh independence study was not carried out.

The results for both flow conditions are presented in Table XXX and allow to draw some interesting conclusions: in both cases wing drag (which includes induced drag) is dominant, making op more than 90% of the total drag. At MSL, the L/D is as high as expected, but the low Reynold's number at 105k ft reduces L/D by more than 50%. The placeholder airfoil (NASA NLF-1) is unsuited for these flow conditions.

Table XX – 3D RANS results.

Parameter	MSL 2deg AoA	105k ft 2deg AoA
C_L	0.891	0.749
$C_{D\ total}$	0.01823	0.03456
L/D	48.88	21.67
$C_{D\ Wing}$	0.01679	0.03200
$C_{D\ Nacelle\ inner}$	0.00032	0.00052
$C_{D\ Nacelle\ outer}$	0.00011	0.00028
$C_{D\ Fuselage}$	0.00055	0.00095
$C_{D\ Struts}$	0.00021	0.00045
$C_{D\ Vertical\ tails}$	0.00025	0.00036

The following conclusions were drawn from this initial study: The aerodynamic design of the RMMP must be driven by the wing's design because the drag of all other components is negligible compared to the wing's drag. The very low Re-number on Mars dictates the use of a custom airfoil to reduce flow separation and drag.

2D Aerodynamic Analysis

A review of low Reynold's number airfoils revealed a lack of high lift airfoils for the flight conditions of the RMMP. Airfoils for human-powered airfoils were considered, but most were optimized for Re > 200,000. Therefore, a new airfoil needed to be developed for the RMMP. This problem was approached by coupling the well-known XFoil code to a multipoint shape optimization routine. The numerically optimized airfoils were then further modified manually to improve the pressure distributions.

While XFoil is a great tool to quickly analyze and compare airfoils, it is lacking in the prediction of drag when compared to a 2D RANS method. Therefore, candidate airfoils were analyzed using a 2D RANS method. Turbulence was simulated with Menter's SST model, and the γ-Re_θ-model is used to simulate boundary layer transition. The 2D flow domain was discretized into 350,000 cells.

At the Reynold's number of the Dash-1 RMMP design, maximum airfoil L/D values ranged from 38 at 16% t/c to 54 at 10% L/D. The low Re conditions take their toll. The target L/D of 44 was not achievable with such limited airfoil performance. The design needed to be changed to obtain better performance. Consequently, it was decided to increase wing Reynolds number by increasing wing chord and the design speed to 150% of the Dash-1 values. A reduction in aspect ratio would allow using an airfoil with a 12% thickness ratio, which is considered a great starting point for further aero-structural optimization.

The optimization process was rerun for the new set of requirements. The resulting airfoil (called FF-RMMP150-12) is shown in Fig. XX. The airfoil's performance is given in table XX and shown in Fig. XX. With a maximum L/D > 60, this airfoil should provide much-improved performance over the initial placeholder airfoil and is therefore chosen for the Dash-2 design.

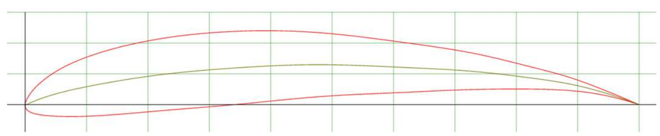

Fig. XX – FF-RMMP150-12. Max thickness 12% at 30.1% chord. Max camber 6.5% at 48.4% chord.

Table XX – FF-RMMP150-12. 2D RANS results.

AoA [deg]	Cl [-]	Cd [-]	Cm [-]	L/D [-]	$L^{1.5}/D$ [-]
-2.5	0.4762	0.01883	-0.1879	25.3	17.5
0.0	0.7366	0.01542	-0.1859	47.8	41.0
2.5	1.0046	0.01682	-0.1835	59.7	59.9
5.0	1.2603	0.02070	-0.1820	60.9	68.4
7.5	1.4625	0.02601	-0.1729	56.2	68.0
9.5	1.5713	0.03257	-0.1597	48.2	60.5
11.0	1.5883	0.04289	-0.1463	37.0	46.7

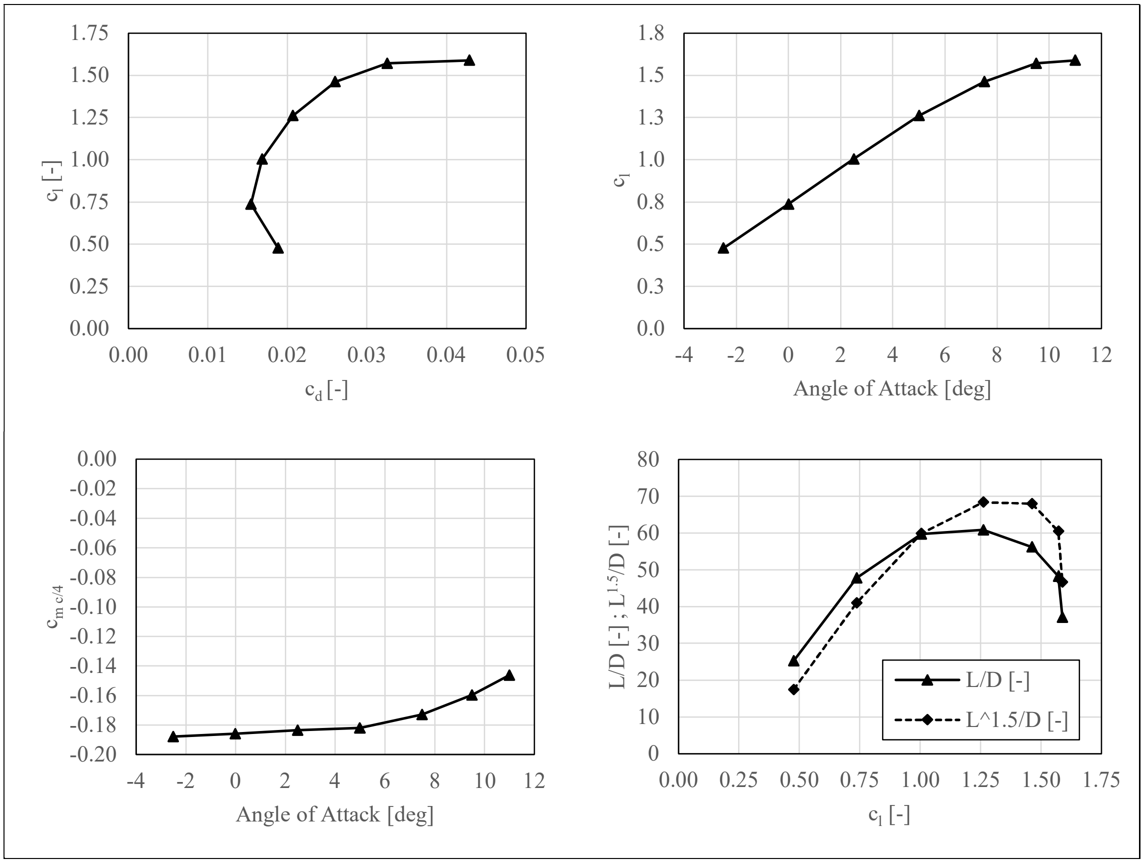

Fig. XX – FF-RMMP150-12. Aerodynamic performance

References

[1] F. Götten, D. F. Finger, M. Marino, C. Bil, M. Havermann and C. Braun, "A Review of Guidelines and Best Practices for Subsonic Aerodynamic Simulations using RANS CFD," in *Asia-Pacific International Symposium on Aerospace Technology - APSIAT 2019*, Gold Coast, Australia, 2019.