Assessment of aerodynamics of low Martian atmosphere within the CIRA program TEDS

Francesco Antonio D'Aniello[1,a *], Pietro Catalano[1,b] and Nunzia Favaloro[1,c]

[1]Cira, Via Maiorise, Capua (CE), Italy

[a]f.daniello@cira.it, [b]p.catalano@cira.it, [c]n.favaloro@cira.it

Keywords: RANS, Low Reynolds Number, Compressible, Martian Atmosphere

Abstract. The space exploration and colonization Roadmap, and the growing interest of the international scientific community toward the Mars colonization, are highlighting the need to develop, or improve to higher TRLs, those technologies enabling human exploration and colonization. In this framework, the CIRA - PRORA research program TEDS has identified some of the most promising technologies and research areas for human/robotic exploration, and human survivability in hostile environments in future space missions. In this contest, Aerodynamics in the Martian low atmosphere, characterized by low Reynolds number and high Mach number, is one of the research areas to investigate. The compressible aerodynamics of low Reynolds number flow (Reynolds number of orders of magnitude 10^4-10^5 and Mach number of 0.2-0.7) characterizes the low altitude Martian atmosphere. The need in the exploration of the Martian surface has increased the interest in this "particular" aerodynamic regime, currently, scarcely investigated, and an assessment of the numerical methods is necessary. Three suitable airfoils for compressible low-Reynolds aerodynamics in Martian atmosphere have been selected through a bibliographic study: Triangular, NACA 0012-34 and Ishii airfoils. The experiments in the low-density CO_2 facility of the Mars Wind Tunnel, at Tohoku University, over a Triangular, NACA0012-34 and Ishii airfoils with global forces and local PSP measurements, have been considered. The CIRA in-house developed flow solver UZEN (Unsteady Zonal Euler Navier-Stokes) code has been applied by employing several turbulence models. The flow over the Triangular airfoil has been simulated inside the wind tunnel and the free air flow over the NACA 0012-34 and Ishii airfoils have been simulated, and in this paper many results are reported.

Introduction

During the last years, the interest of the international scientific community in space exploration and colonization is growing up, particularly toward Mars. For this scope the CIRA-PRORA research program TEDS [1] has identified some of the most promising technologies and research areas for human/robotic exploration, and human survivability in hostile environments in future space missions. Within this program, focusing on Mars exploration and colonization, the study of Aerodynamics in the Martian low atmosphere, characterized by low Reynolds number (10^4 - 10^5) and high Mach number in the compressible or transonic range (0.2 - 0.7), is one of the research areas to investigate. The task concerns the evaluation of the aerodynamic characteristics, of airfoils and wings, in the low Martian atmosphere. Numerical results will also support the feasibility study of a Martian rotorcraft for future survey and exploration missions.

Unfortunately, the pair of compressible/transonic Mach and low Reynolds does not occur in the Earth's atmosphere which is characterized by the incompressible regime. For this reason, low-Reynolds number compressible flows were scarcely investigated so far, and thus the experimental data of airfoils, flying in this Aerodynamics, are very limited. Only NASA and JAXA agencies have experimentally studied this aerodynamic regime as in ***Errore. L'origine riferimento non è stata trovata.***, therefore, an assessment of the numerical methods has been necessary.

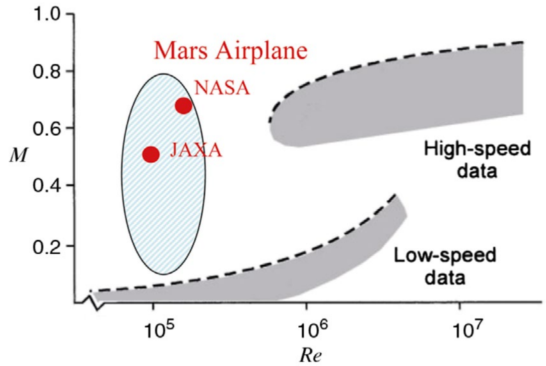

Figure 1 Martian atmospheric flight [2,3].

RANS numerical simulations through the CIRA built in-house UZEN code has been conducted on three suitable airfoils, for compressible low Reynolds aerodynamics in Martian atmosphere, that have been selected through a bibliographic study: Triangular, NACA 0012-34 and Ishii airfoils. The experiments in the low-density CO_2 facility of the Mars Wind Tunnel of Tohoku University over a NACA0012-34, Triangular and Ishii airfoils (sketched in Fig. 2, considering [2,4,5], respectively) with global forces and local PSP measurements, have been considered to first assess the UZEN code.

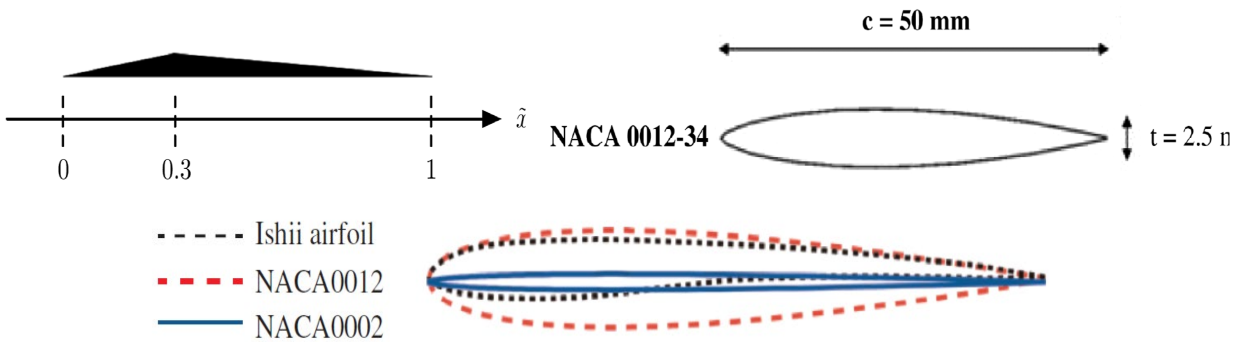

Figure 2 Triangular (top left), NACA0012-34 (top right) and Ishii airfoils (bottom).

Mars Low atmosphere and Aerodynamics

Martian low atmosphere is more rarefied than Earth's one, in fact it mostly consists of carbon dioxide CO_2 (95%) and it is characterized by low pressure ($p \sim 0.0075 \times 101.3$ kPa) low density ($\rho \sim 0.017$ kg/m^3) and low temperature, at the surface, respect to the Earth surface. In the low Reynolds number compressible regime, the flow on the upper wing surface is prone to separate forming the laminar separation bubble (LSB), and after the transition zone the flow reattaches in turbulent manner (as shown in Fig. 3). This complicated flow field scenario strongly affects aerodynamic performances of airfoils and wings. Because of these unusual flow characteristics, the airfoil shape largely impacts on the aerodynamic characteristics, in fact in [3,6] it has suggested three shape characteristics involving high aerodynamic performances in low Reynolds number compressible regime:

- sharp leading edge to fix the separation point at the edge and can improve its Reynolds-number dependence on the aerodynamic performance;
- flat upper surface to reduce the separation region;
- cambered airfoil to gain a higher lift than a symmetric airfoil.

Following the trace of prescribed suggestions, Triangular, NACA 0012-34 and Ishii airfoils have been selected to be numerically simulated.

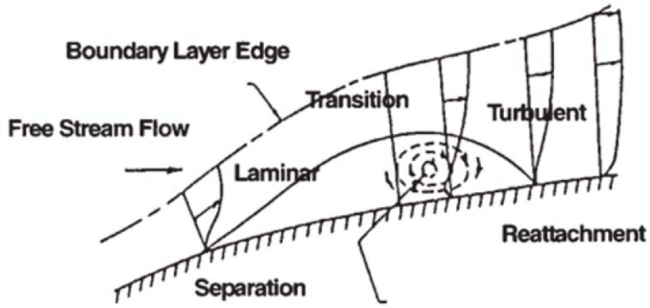

Figure 3 Flow field development when separation bubble occurs [7,8].

Numerical method

The numerical analysis is conducted by using the CIRA in-house code UZEN. The code UZEN [9] solves the compressible 3D steady and unsteady RANS equations on block-structured meshes. The spatial discretization adopted is a central finite volume formulation with explicit blended 2nd and 4th order artificial dissipation. The dual-time stepping technique is employed for time accurate simulations [10,11]. The pseudo-time integration is carried out by an explicit hybrid multistage Runge-Kutta scheme. Classical convergence acceleration techniques, such as local time stepping and implicit residual smoothing, are available together with multigrid algorithms. Turbulence is modelled by either algebraic or transport equation models [12]. Structured multi-block grids were built by using ICEM CFD© commercial code for all the selected airfoils. Both RANS and URANS numerical simulations were conducted to reproduce the MWT experimental data collected in the selected bibliography for all three airfoils, with large interest in the aerodynamic performance coefficients, i.e. lift coefficient (C_L) and drag coefficient (C_D), to better understand how the aerodynamic performance change in the Mars atmosphere respect to the Earth one.

Triangular wing has been simulated within the MWT, while NACA 0012-34 and Ishii airfoils has been exclusively simulated in bi-dimensional domains. In Table 1, the level of grid mesh and the number of cells, for each level and for the three considered airfoils, are listed. Where not specified, the number of cells in spanwise direction is equal to 1 (i.e. nk = 1); otherwise the choice of nk is due to the tri-dimensional grid construction.

Table 1 Grid levels and number of cells (ni × nj × nk) for Triangular, NACA 0012-34 and Ishii airfoils.

	1st lev	2nd lev	3rd lev	4th lev
Triangular	2×10^6 (nk = 64)	15×10^6 (nk = 130)	/	/
NACA 0012-34	200×25 = 5000	400×50 = 20000	800×100 = 80000	1600×200 = 320000
Ishii	64×32 = 2048	128×64 = 8192	256×128 = 32768	512×256 = 131072

Numerical results and discussion

In Fig. 4, the dimensionless wall distances (y^+) on Triangular wing (M=0.5, Re=1.0×10^4, α=5°), and over the upper region of NACA 0012-34 (M=0.2, Re=1.1×10^4, α=0°) and Ishii (M=0.2, Re=2.3×10^4, α=0°) airfoils, obtained by RANS calculations, are reported.

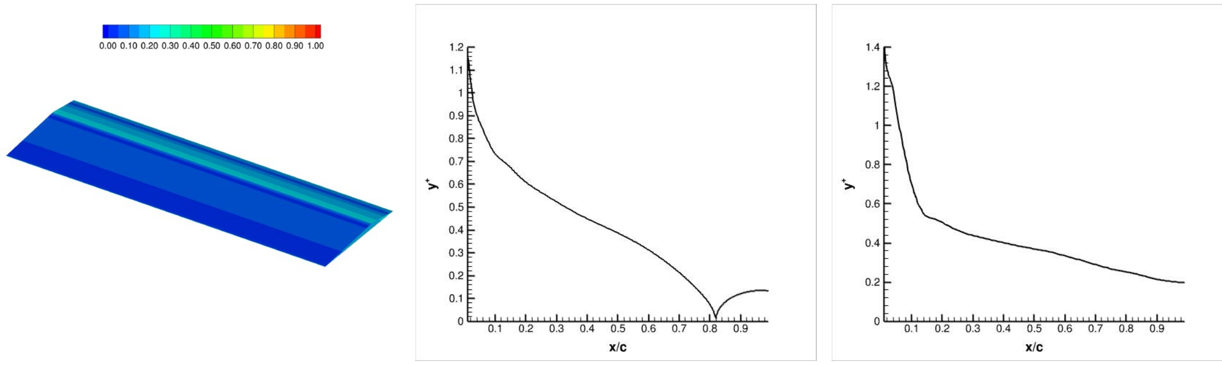

Figure 4 Dimensionless wall distance (y^+) on Triangular wing (left), over the upper region of NACA 0012-34 airfoil (centre) and over the upper region of Ishii airfoil (right).

Through the comparison with the available experimental data, numerical results for the three selected airfoils, globally confirm experimental reports, highlighting that the Mars aerodynamic regime strongly affects aerodynamic performances of airfoils. In fact, looking at Fig. 5, Fig. 6 and Fig. 7, convergence simulations have been discretely reproduced the global trend of polar curves or C_D curves for all the Reynolds and Mach numbers considered. The differences between numerical results and MWT experimental data are due to the used computational grids (bi-dimensional in the case of NACA 0012-34 and Ishii) because their coarsening or design (Ishii trailing edge is open). Turbulence models were not always be able to reproduce exactly the very complex flow field (vortex structures, laminar separation bubble, etc) generated around the wing or on the airfoils. For the Triangular wing (refer to Fig. 5), at Reynolds number equal to 1.0×10^4, numerical results are in good agreement with the experiments at $\alpha = 5^\circ$, at all the three Mach numbers considered. As the incidence increases, the comparison gets worse. For NACA 0012-34 airfoil (refer to Fig. 6), polar curves are partially reproduced due to the lack of numerical convergence. Numerically reproduced polars are slightly underestimated in terms of C_D than those experimentally recorded. The comparison between numerical results and experimental data slightly improves at high Mach numbers, perhaps as a result of the compressibility effect introduced. At Mach number equal to 0.61, a good agreement with experimental data is reached through the $\kappa - \omega$ SST. For Ishii airfoil (refer to Fig. 7), a globally slight underestimation is detectable in terms of C_D with respect to the experimental data. The $\kappa - \omega$ turbulence models used does not allow to reproduce perfectly the complex flow field that occurs on this airfoil, already at low angles of attack. The $\kappa - \omega$ SST model gave a good agreement with experimental data, and also respect to the LES numerical simulations reported in literature, for almost all the considered incidences.

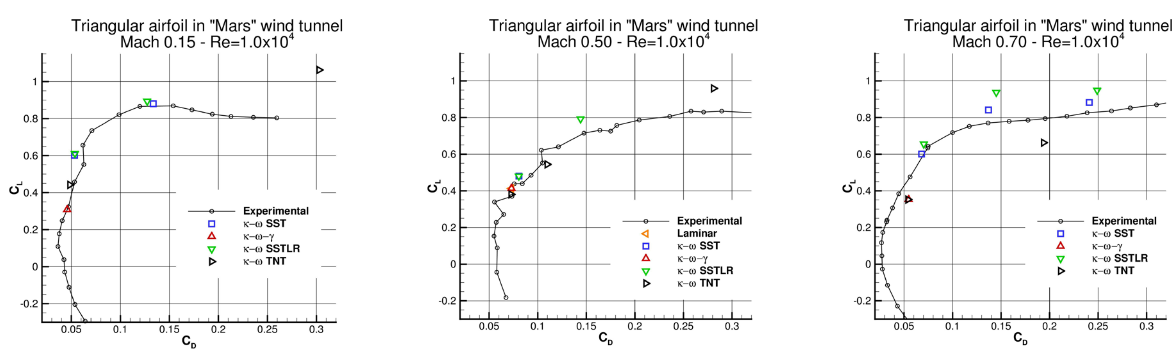

Figure 5 Triangular wing: Drag Polars at Reynolds number 1.0×10^4, at $M = 0.15$ (left), $M=0.50$ (centre) and $M=0.70$ (right), calculated with different $\kappa - \omega$ turbulence models.

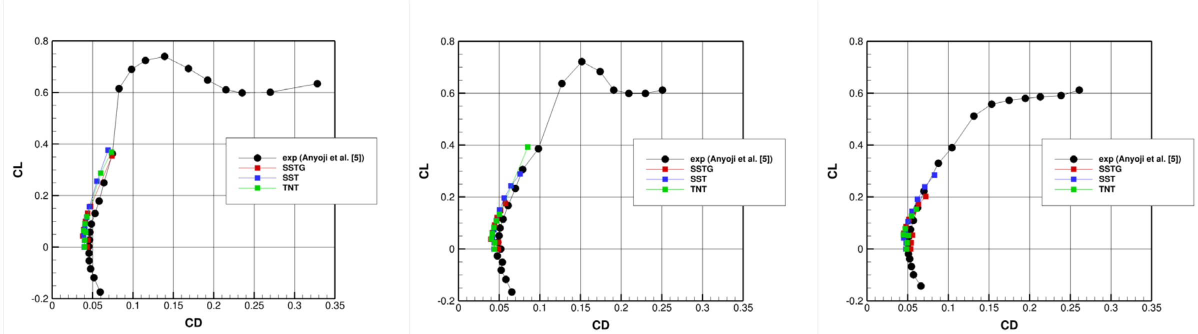

Figure 6 NACA 0012-34 airfoil: Drag Polars at Re = 1.1 × 10^4, at M = 0.20 (left), M=0.48 (centre) and M=0.61 (right), calculated with different κ − ω turbulence models.

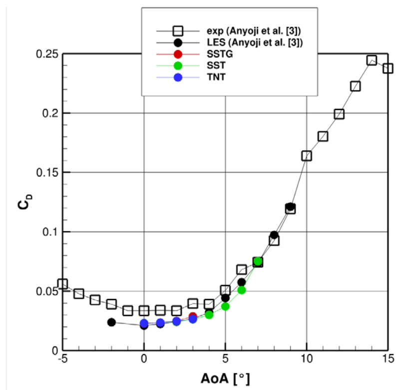

Figure 7 Ishii airfoil: Drag Coefficient versus angle of attack at Reynolds number 2.3 × 10^4 and at Mach number 0.20, calculated with different κ – ω turbulence models.

Focusing on Triangular airfoil, the flow field around the wing, inside the wind tunnel, provided by the numerical simulations is actually very complex, above all at high incidence. Flow structures forming at the side-ends of the body and developing in the wake can be also appreciated in Fig. 8 that, following the Q-criterion, reports an iso-surface of $Q = \frac{1}{2}\left(\Omega_{i,j}\Omega_{i,j} - S_{i,j}S_{i,j}\right)$, where $\Omega_{i,j}$ is the vorticity magnitude and $S_{i,j}$ is the rate of strain (Q-criterion defines vortices as areas where the vorticity magnitude is greater than the magnitude of the rate of strain). The vortex regions in the central part are visible. It can be also noted as the side-end structures tend to disappear at the highest Reynolds number.

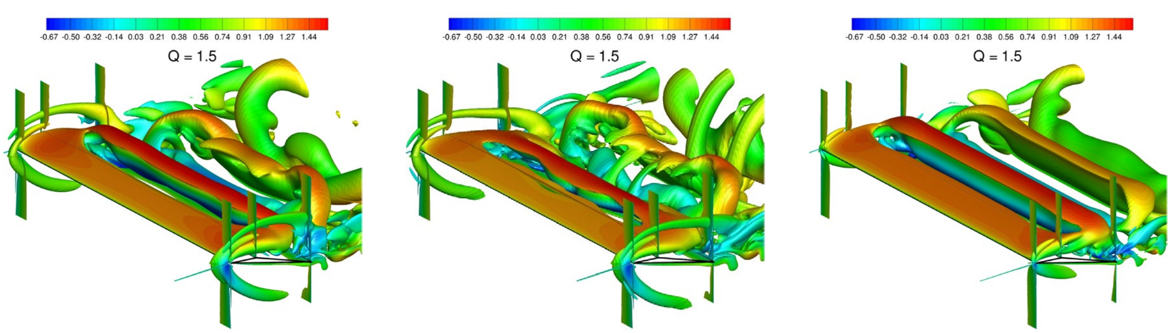

Figure 8 Iso-surface of Q at α = 15°, M=0.15, Re=3.0 × 103 (left), M=0.50, Re=3.0 × 103 (centre), M=0.15, Re=1.0 × 104 (right).

Summary

Numerical simulations conducted with CIRA built in-house UZEN code through all the employed κ-ω turbulence models, have been partially reproduced the flow field around the wing in the wind tunnel (Triangular airfoil) and around the airfoils in free air (NACA0012-34, Ishii) and with a global good agreement with the experimental data in terms of aerodynamic performances (i.e. lift and drag coefficients), especially at low and medium incidences.

Although the scarce 3D simulations conducted on the wing based on the Triangular airfoil, they allow to underline the strongly 3D structure of the flow field that influences the aerodynamic performance degradation, above all at high incidences.

NACA 0012-34 and Ishii are more feasible to fly airfoils than the Triangular one. Their design has been thought to fly at high incidences in a low-Reynolds environment and, at the same time, to allow the flow to reattach downstream the formation of the laminar separation bubble.

The influence of the Mach number has been also investigated. The numerical results have shown that the increase in Mach numbers seems to energize the flow, that is more able to withstand the adverse pressure gradients and becomes less prone to the separation.

References

[1] N. Favaloro, G. Saccone, F. Piscitelli, R. Volponi, P. Leoncini, P. Catalano, A. Visingardi and M. C. Noviello, “Enabling Technologies for Space Exploration Missions: The CIRA-TEDS Program Roadmap Perspectives,” Aerotecnica Missili & Spazio, 2023. https://doi.org/10.1007/s42496-023-00159-4

[2] Anyoji, Numata, Nagai and Asai, “Effects of Mach Number and Specific Heat Ratio on Low-Reynolds-Number Airfoil Flows,” AIAA Journal, vol. 53, no. 6, 2015. https://doi.org/10.2514/1.J053468

[3] F. W. Schmitz, “Aerodynamics of the Model Airplane Part1,” NASA, Technical Rept., NASA-TM-X-60976, 1967.

[4] Munday, Taira, Suwa, Numata and Asai, “Nonlinear Lift on a Triangular Airfoil in Low-Reynolds-Number Compressible Flow,” Journal of Aircraft, 2015. https://doi.org/10.2514/1.C032983

[5] Anyoji, Nonomura, Aono, Oyama, Fujii, Nagai and Asai, “Computational and Experimental Analysis of a High-Performance Airfoil Under Low-Reynolds-Number Flow Condition,” Journal of Aircraft, vol. 51, no. 6, 2014. https://doi.org/10.2514/1.C032553

[6] F. W. Schmitz, “The Aerodynamics of Small Reynolds number,” NASA TM, 1980.

[7] Tsukamoto, Yonemoto, Makizono, Sasaki, Tanaka, Ikeda and Ochi, “Variable-Pressure Wind Tunnel Test of Airfoils at Low Reynolds Numbers Designed for Mars Exploration Aircraft,” Trans. JSASS Aerospace Tech. Japan, vol. 14, no. 30, pp. 29-34, 2016. https://doi.org/10.2322/tastj.14.Pk_29

[8] Rinoie and Kamiya, “Laminar Separation Bubbles Formed on Airfoils,” Journal of Japan Society of Fluid Mechanics, no. 22, pp. 15-22, 2003.

[9] Catalano and Amato, “An evaluation of RANS turbulence modelling for aerodynamic applications,” Aerospace Science and Technology, vol. 7, no. 7, pp. 493-509, 2003. https://doi.org/10.1016/S1270-9638(03)00061-0

[10] Marongiu, Catalano, Amato and Iaccarino, “U-ZEN: A computational tool solving U-RANS equations for industrial unsteady applications,” in 34th AIAA FluidDynamics Conference and Exhibit, 2004. https://doi.org/10.2514/6.2004-2345

[11] Capizzano, Catalano, Marongiu and Vitagliano, "URANS modelling of turbulent flows controlled by synthetic jets," in 35th AIAA FluidDynamics Conference and Exhibit, 2005. https://doi.org/10.2514/6.2005-5015

[12] Catalano, Mele and Tognaccini, "On the implementation of a turbulence model for low Reynolds number flows," Computers and Fluids, vol. 109, pp. 67-71, 2015. https://doi.org/10.1016/j.compfluid.2014.12.009