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Subsonic and Transonic Low-Reynolds-Number Airfoils with Reduced Pitching Moments

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Abstract

PRESENTLY, there is interest in the development of high-altitude long-endurance (HALE) subsonic airplanes for communications relaying, remote sensing, drug enforcement, and weather monitoring, and very-high-altitude transonic airplanes for atmospheric sampling at altitudes of 100,000 ft and above. The successful development of such airplanes depends critically on the aerodynamic force and moment characteristics of the wing section shapes.[1] Here, a subsonic airfoil design for the HALE mission and a transonic airfoil design for the very-high-altitude mission are presented. Also, the design method is briefly outlined. The subsonic airfoil is designed for a lift coefficient c_l = 1.4 at a chord Reynolds number $Re = 7 \times 10^5$ and a very low Mach number M. The transonic airfoil is designed for c_l = 1.0 at $Re = 5 \times 10^5$ and M = 0.7. Both airfoils are developed to perform as well or better than previously developed airfoils. However, the present airfoils are generated while constraining the pitching moment in order to reduce the torsional loads in the high-aspect-ratio wings.

Contents

A new design method that combines the airfoil analysis code ISES of Drela and Giles[2] and a modified version of the quasi-Newton minimization algorithm QNMDIF of Gill et al.[3] is applied to generate the section shapes. The ISES code is robust and provides accurate predictions of lift c_l, drag c_d, and pitching-moment (about the quarter-chord point $c/4$) c_m coefficients at low Reynolds numbers. The unique feature of the design method is that it allows the minimization of both viscous and wave drag. Previous efforts to couple gradient optimization techniques with viscous-inviscid interaction methods have often been inhibited by their inability to calculate the viscous drag without the presence of significant numerical noise. The simultaneous solution of both the inviscid and viscous flowfields in the ISES code allows for the rapid convergence to machine accuracy, thereby guaranteeing a smooth design space.

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Airfoil shapes are modified by placing several different perturbation functions at various stations around the airfoil.[1,4] The design variables of the optimization problem are the linear coefficients of these perturbation functions. The objective function of the problem is c_d or c_d/c_l. Since the optimization method is unconstrained, constraints for properties such as c_m and the airfoil maximum-thickness-to-chord ratio t/c are added to the objective function in the form of quadratic penalty functions. In the present study, the target value for the nose-down pitching-moment coefficient is obtained in an iterative manner. The target value is slowly reduced until a limit value is reached below which the performance characteristics of the airfoil are degraded by the pitching-moment constraint.

The transonic airfoil that is developed using the previously described design method is designated LRT 70-10-14: low Reynolds-number transonic airfoil with a design Mach number of 0.70, a design lift coefficient of 1.0, and a t/c = 0.14. In Fig. 1, the airfoil and its predicted pressure distribution at the design conditions are presented. The undercut lower surface in the nose region reduces the velocities along the lower surface near the leading edge and shifts the center of pressure forward, which results in the desired reduction in the nose-down pitching moment. In Fig. 2 the predicted section characteristics are presented for both the LRT airfoil and the OW 70-10-14 airfoil. The OW airfoil is selected for comparison because it represents the state-of-the-art in terms of wing section shapes for very-high-altitude airplanes. At the design conditions and assuming free boundary-layer transition, a comparison shows that the drag of the LRT airfoil is 6% less (c_d = 0.0137 vs c_d = 0.0146) and the nose-down pitching moment is 13% less (c_m = −0.1608 vs c_m = −0.1860). At

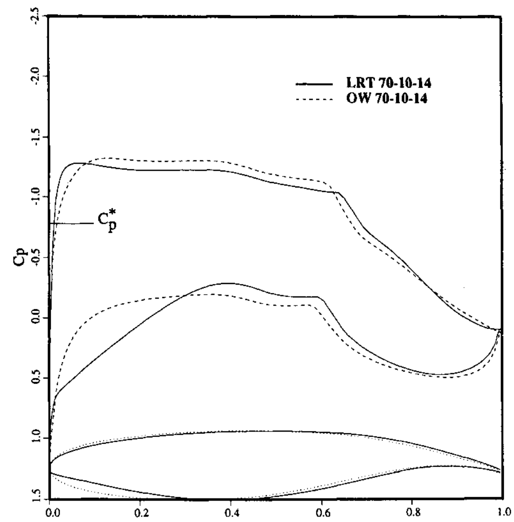

Fig. 1 Geometry and pressure distribution of LRT 70-10-14 and OW 70-10-14 for c_l = 1.0, M = 0.7, $Re = 5 \times 10^5$, and free transition.

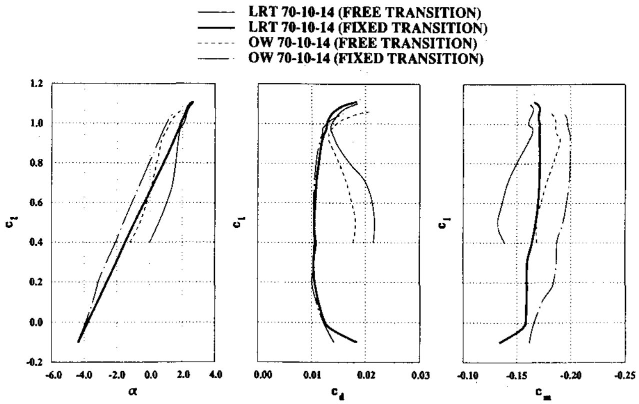

Fig. 2 Comparison of performance of LRT 70-10-14 and OW 70-10-14 for $M = 0.7$ and $Re = 5 \times 10^5$ with both free transition and fixed transition (trip location $(x/c)_u = 0.70$, $(x/c)_l = 0.53$).

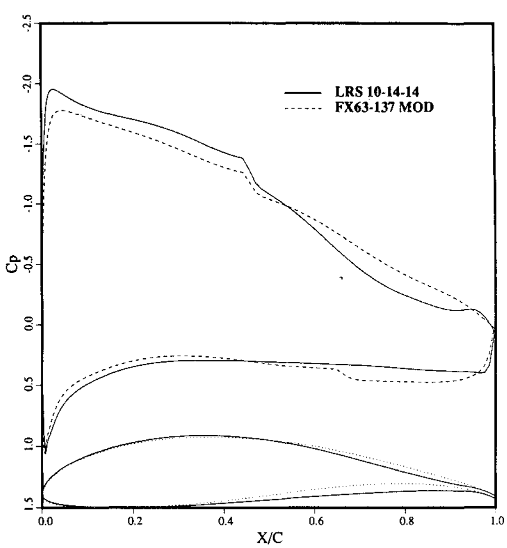

Fig. 3 Geometry and pressure distribution of LRS 10-14-14 and FX63-137 Mod for $c_l = 1.4$, $M = 0.1$, $Re = 7 \times 10^5$, and free transition.

lift coefficients below 1.0, both airfoils demonstrate poor performance characteristics. The high drag values are primarily caused by laminar separation at the onset of pressure recovery on both the upper and the lower surface for both airfoils.

The off-design performance characteristics can be improved by incorporating a cruise flap and/or a transition control device.[1] In Fig. 2 the performance characteristics of both the OW and the LRT airfoil with transition trips at a fixed location can be compared with those of the airfoils with free transition. Significant improvements in the drag polars and a straightening of the lift curves are evident. Also, note that the transition control produces only a minor improvement in the drag of the LRT airfoil at the design point, demonstrating that the design method (using the free-transition option) does a good job minimizing laminar separation and, thus, drag.

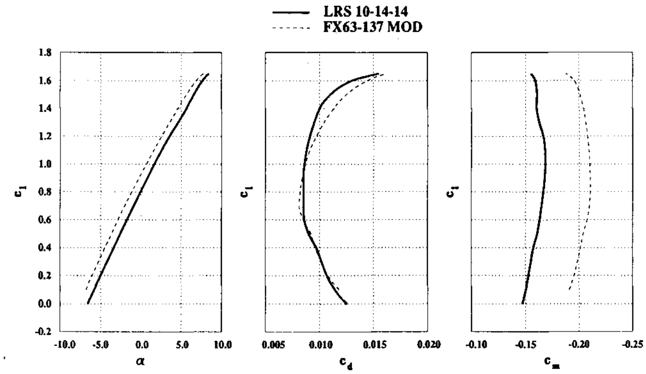

Fig. 4 Comparison of performance of LRS 10-14-14 and FX63-137 Mod for $M = 0.1$, $Re = 7 \times 10^5$, and free transition.

The design method is also applied to generate the low-speed section shape LRS 10-14-14 (low Reynolds-number subsonic airfoil for $M = 0.10$ and $c_l = 1.4$ with a t/c of slightly more than 14%). A comparison of the performance characteristics of the LRS airfoil and the baseline FX63-137 Mod airfoil indicates a 11.5% reduction in drag ($c_d = 0.100$ vs $c_d = 0.0113$) and a 21.5% drop in the nose-down pitching moment ($c_m = -0.1602$ vs $c_m = -0.2042$) at the design conditions. Note that the FX63-137 airfoil[5] has a zero-thickness trailing edge and is slightly modified to obtain a finite trailing-edge thickness of 0.005c. In Fig. 3 a comparison of the pressure distributions shows that the reductions in the drag and the pitching moment mainly result from the introduction of a concave pressure recovery along the upper surface and a backward shift of the onset of pressure recovery along the lower surface. The results in Fig. 4 indicate that the LRS airfoil has a substantially lower nose-down pitching moment than the Wortmann airfoil at design as well as off-design conditions.

Acknowledgments

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