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Analysis of General-Aviation Aircraft Wing Sections with Drooped Leading Edges

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The addition of a leading-edge extension that droops the leading edge of a general aviation aircraft wing, akin to a deployed slat, increases the camber of the wing and thus has the potential to increase its lifting capability during takeoff. The aircraft wing under consideration in this study is that of the Cessna Caravan. An analysis of the root and wing-tip sections and two proposed wing modifications was carried out in order to gain insight into the aerodynamic performance characteristics of the proposed alterations. The single-element original- and modified-wing root and tip sections were analyzed in free air using the two-dimensional Euler/coupled boundary-layer code MSES. A comparison of computed results with experimental data of the airfoils in the same class as those of the Caravan indicated that although MSES overpredicts the lift coefficient it accurately predicts the change in maximum lift coefficient with Reynolds number indicating that MSES could be used to evaluate the relative performance of the airfoils in question. Further analyses suggested that the overprediction of lift is a consequence of the implementation of the transition model in MSES. The two wing modifications, the AOG-series and the JS-series airfoils, showed the potential to increase the lifting capability of the Caravan wing. One significant observation to be made from all of the results on the drooped leading edge is that the increase in camber of the airfoil dramatically increases the nose-down pitching moment of the airfoil. It was also found that the sensitivity of the airfoil to freestream turbulence can also be affected by the proposed wing modifications.

Nomenclature

A	=	planform area of wing
C_d	=	section drag coefficient
C_l	=	section lift coefficient
$C_{l_{max}}$	=	section maximum lift coefficient
C_m	=	section pitching moment coefficient about 1/4-chord
c	=	airfoil chord
L	=	lift of wing
Ma	=	freestream Mach number
n	=	limiting exponent for transition model
Re	=	section Reynolds number
V	=	freestream velocity
α	=	angle of attack
ρ	=	air density

Introduction

THE performance of an aircraft's wing at low speeds and high angles of attack is critical in determining the takeoff and landing characteristics of the aircraft. To enhance a wing's capability at takeoff and landing, many larger planes use slats deployed from the leading edge along with flaps extending from the trailing edge. These devices increase both the wing chord and the camber of the wing section, both beneficial to increasing the lift of the wing. Smaller general-aviation planes employ flaps but lack leading-edge devices. This present study explores the possibility of altering the leading edge of a general-aviation wing, in particular that of the Cessna Caravan, through the addition of a permanent leading-edge modification/extension, which droops the leading edge analogous to that of a deployed slat. Experiments and model-scale testing[1–3] have shown that drooping a portion of the leading edge can be beneficial to the aerodynamic characteristics of a general-aviation aircraft at high angles of attack and into stall. This work is part of a larger effort by A.O.G. Air Support, Inc. (AOG) to retrofit existing Caravan aircraft with modifications aimed at improving the aircraft's performance over the entire flight envelope with particular emphasis on takeoff and landing.

A.O.G. Air Support, Inc., of Kelowna, British Columbia, Canada is a company that designs, fabricates, and installs custom aircraft modifications. It started in the business with the development of a new leading edge for the de Havilland DHC-2 Beaver. One of its current foci is the modification of the Cessna Caravan on wheels with the aim of having a maximum takeoff weight (MTOW) of 4082 kg (9000 lb) with a stall speed of 70 KCAS (36 m/s) without flaps deployed. The 208 and 208A aircraft currently have a MTOW of 3792 kg (8360 lb) for 0-deg flaps with a stall speed of 75 KCAS (38.6 m/s). AOG will accomplish this through the modification of the wing, the addition of winglets and changes to the propulsion system. To meet the project's goals, the lift of the wing must be increased by approximately 400 kg (1000 lb). This can be realized by increasing the size of the wing area through an increase in the wing span or chord (or both) and/or increasing the lift coefficient of the wing by modifying the camber of the wing. The combination chosen was that of lengthening the chord and increasing the camber of the wing by adding a leading-edge droop[1] along the entire span of the leading edge (Fig. 1).

Cessna Aircraft Corporation[†] developed the 208 Caravan in the early 1980s. It is a single-engine, braced high wing, general-aviation turboprop aircraft that fits a large variety of utility roles including flying passengers and cargo to remote locations. The 208 Caravan is a 11.46-m aircraft with a 15.88-m wing span.[4] The wing has a 1.64-m mean aerodynamic chord with a 1.98-m chord at the root and a 1.22-m chord at the tip. The root airfoil section is a NACA 23017.424 changing to a NACA 23012 at the tip through a twist of roughly 3 deg.

As an initial examination of the aerodynamic performance of the new AOG Caravan wing, the Aerodynamics Laboratory of the Institute for Aerospace Research, National Research Council Canada, studied the characteristics of the root and tip airfoil sections of the original and two modified wings using the two-dimensional computational-fluid-dynamics (CFD) code MSES.[5] The airfoils were studied as single-element airfoils (i.e., no flaps) as that was part of the overall aim of the AOG project. MSES uses a coupled

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[†]Data available online at www.cessna.com.

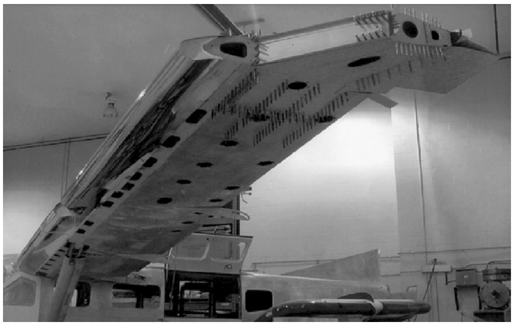


Fig. 1 AOG-series leading edge of Caravan (courtesy of AOG Air Support, Inc.).

Euler/boundary-layer algorithm that includes a transition model and is designed to accurately predict transonic flows and low-Reynolds-number sections [i.e., Reynolds number $\mathcal{O}(10^5)$]. The results of these airfoil analyses and supporting validation and verification work are presented in this paper. Although the focus of the wing modification is the increase in performance of the wing at moderate to high angles of attack, the price of that increase should not come at the expense of the cruise performance of the wing. Thus, the various airfoils were examined at cruise conditions, and those results are also presented here.

Analysis Method

Two-Dimensional Analysis Tool

The wing sections of the current study were analyzed with the two-dimensional airfoil design and analysis CFD code MSES. This program has been designed to simulate the flow over transonic airfoils and over low-Reynolds-number sections. It has been found to be a robust program providing accurate predictions of the aerodynamic coefficients including the nonlinear region approaching stall. A brief summary of this tool follows with more complete details found elsewhere.[5,6]

MSES solves the flow around multi-element airfoils through the strong coupling of an Euler solver and an integral boundary-layer code. The global nonlinear system is solved via a Newton method providing converged solutions quickly and efficiently. The interface between the two algorithms is handled by the displacement thickness concept in that the surface of the airfoil defining the geometry being simulated by the inviscid solver is displaced outward by the thickness of the boundary layer calculated by the viscous code. The two-equation boundary-layer formulation will predict and compute flow separations making it possible to use MSES at higher angles of attack. Incorporated into the viscous analysis is a modified e^n-transition model. In this model, transition is based only on the Tollmien–Schlichting wave with the maximum local amplification factor.[6] The transition location can also be fixed a priori to any given location including the leading edge, making the simulation a calculation of a fully turbulent flowfield. This combination of algorithms has made MSES a useful aerodynamic performance predictor.

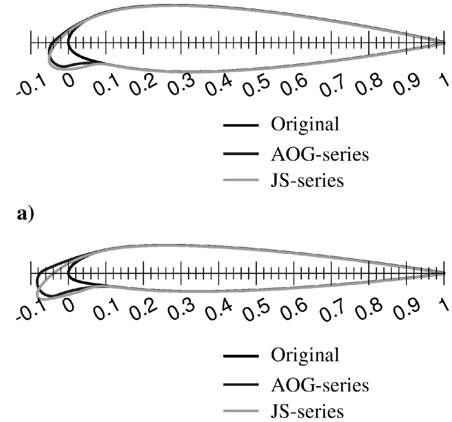
Two-Dimensional Airfoil Sections

Three different sets of airfoils were analyzed to discover their relative aerodynamic performance. Each set included the root and wing-tip sections. The first set was the original Caravan geometry. The remaining two sets, herein called AOG-series and JS-series, were the root and wing-tip airfoil pair with modifications to their respective leading edges.

Cessna Caravan Airfoil Sections

The Cessna wing has a linear taper from a NACA 23017.424 at the root to a NACA 23012 at the tip. The analyses performed by NRC focused solely on these two wing stations as it was believed that studying these two sections, the root and the tip, would provide an indication of the performance of the three-dimensional wing.

The 230-series mean line on which these two airfoils are based has the maximum camber of the mean line at 15%c. The outlines for these airfoils can be found in Fig. 2.



b) Tip airfoil sections

Fig. 2 Original and modified Caravan wing sections.

Drooped Leading Edge Airfoils

Two different types of leading-edge droops were explored to determine their relative performance. A constant leading-edge extension was applied to the wing, meaning the percentage increase in chord was smaller at the root compared to the tip. With the addition of the constant leading-edge section, the twist of the wing was reduced slightly.

The first set of modifications to the leading edge, the AOG-series, consisted of linear extensions of the airfoil camber. These airfoils can also be found in Fig. 2. To analyze these airfoils with MSES, each was normalized to a chord of unity with zero pitch. Although it is true that any differences in the relative full-scale wing section performance can be in part attributed to differences in chord length, normalizing all of the airfoils in the same manner highlights the affects of the airfoil shape, in particular its camber.

The leading-edge droop is conceptually an increase in camber of the airfoil. This led to the thinking that a blending of the leading edge of a high camber airfoil with the main body of the existing Caravan wing section might provide a reasonable compromise between the two geometries. The second set of modified airfoils, the JS-series, was obtained by combining the existing NACA 23012 and 23017.424 of the Caravan wing and a high-camber NACA 4 digit series airfoil of similar thickness. A comparison of the JS-series airfoils with the original and AOG-series sections can also be found in Fig. 2.

Results and Observations

The aerodynamic performance of the original Cessna Caravan root and tip-wing sections along with two modifications to each section have been studied numerically. Of the numerous possible means to examine the performance of these airfoils, this paper focuses on the lift, drag, and pitching-moment coefficients. In particular, results are presented in terms of the lift curve (C_l vs α) and the drag and pitching-moment polars (C_d vs C_l and C_m vs C_l, respectively). For the study and comparison of the various Caravan root sections, all lift coefficients have been scaled by the maximum lift coefficient for the original Caravan root section as computed with natural transition. Similarly, all tip lift coefficients have been scaled by the Caravan tip $C_{l_{\max}}$. As a precursor to studying the Caravan wing sections, the ability of MSES to study the NACA 230-series of airfoils was examined by comparing computed results to historical experimental data. Those comparisons as well as a study of the effect of varying the transition model are presented. Finally, the aerodynamic characteristics of the six Caravan airfoils at cruise conditions are documented.

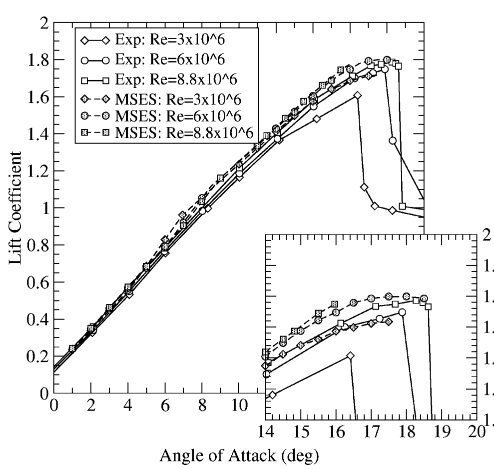
Numerical Validation

To determine the ability of MSES to predict the aerodynamic characteristics of the Caravan wing sections (and their modifications), several tests were carried out on NACA 230-mean line airfoils and the results compared to historical experimental data. This data set is a compendium of aerodynamic data put together by Abbott and vonDoenhoff,[7] summarizing the original experiments performed by NACA. From the available performance curves, the closest airfoils in shape to those on the Caravan were the NACA 23012 and the 23018, and it is against these data that the MSES calculations were compared. For brevity, only the NACA 23012 results are presented here.

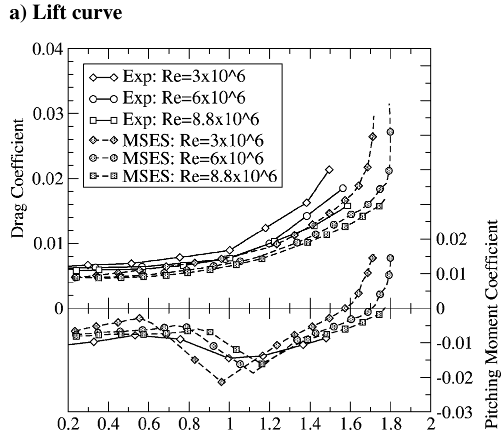
Experimental data for the NACA 23012 are available at Reynolds numbers of 3, 6, and 8.8×10^6. Numerical results were obtained for these Reynolds numbers with the freestream Mach number set to 0.1. The freestream turbulence intensity was set to that of the NACA Langley Low Turbulence Pressure Tunnel at 0.015%. Plots of the lift curve, drag polar, and pitching-moment polar for the NACA 23012 experimental and numerical data can be found in Fig. 3. Note that experimental pitching-moment data are presented for only one Reynolds number as data at different Reynolds numbers were indiscernible on the experimental graphs from the Reynolds numbers included in the figure. The figure shows that although MSES consistently overpredicts the lift and in particular the maximum lift coefficient the correct trend in $C_{l_{max}}$ for increasing Reynolds number is captured. This would tend to indicate that although the absolute value of the lift coefficient might be in slight error the relative differences in the performance of the airfoils in question can be predicted by MSES. The NACA 23012 airfoil is unique in that it experiences a leading-edge stall while the surrounding airfoils in this series exhibit a trailing-edge stall.[8] Recent experimental results[9] compare favorably to the historical data confirming the airfoil's aerodynamic characteristics. This unique performance makes predicting its aerodynamic coefficients a challenge. As an interesting aside, pilots report that the Caravan can experience an instant stall (personal communication, C. Hunter, AOG Air Support, Inc.), which might be a consequence of the abrupt stall behavior of its tip airfoil.

With the overprediction by MSES in lift of the NACA 23012 comes an overestimation of the drag of the airfoil at large angles of attack although again the correct trends with varying Reynolds number are shown. Discrepancies in the computed and experimental values of the pitching moment should be viewed with caution because of the imprecise extraction of data from experimental graphs. Having noted this however, the shape of the curves is similar, showing the same dip in pitching moment at moderate angles of attack.

Although MSES overpredicts the various coefficients at high angles of attack, the relative differences are captured well. It is this consistent observation that is used as a framework for comparing the original Caravan wing sections and its modifications. A possible explanation for the behavior of MSES is presented in the next section.



a) Lift curve



b) Drag and pitching-moment polars

Fig. 3 Aerodynamic performance of the NACA 23012.

Transition Modeling

One aspect of MSES that makes it a powerful predictive tool for the class of airfoils being analyzed in this study is its ability to model transition. The code incorporates a modified e^n model to handle the transition from laminar to turbulent flow. In this model, instability waves in the boundary layer are tracked, and when their amplification exceeds a certain value (nominally e^n times their initial magnitude normally with $n = 9$) the flow is said to turn turbulent. As a simplification to the model, MSES tracks only a local subset of the instability waves.

By varying the value of n, one can play with the susceptibility of the boundary layer to disturbances, which can be viewed analogously as altering the level of freestream turbulence. The behavior of an airfoil with a boundary layer that is more sensitive to disturbances (smaller values of n) will exhibit behavior similar to that of the same airfoil in a higher level of freestream turbulence, that is, the length of laminar run will tend to be shorter with an accompanying reduction in lift. Likewise, a less sensitive boundary layer (larger values of n) will have a longer laminar run viewed alternatively as an airfoil in lower freestream turbulence. It was through modification of n that the freestream levels of turbulence were set in the previous experimental validation exercise.

The transition model in MSES allows for the setting of the transition location to a predetermined location. Results for the various airfoils analyzed in this project include simulations in which the transition location was set to $1\%c$ on the upper surface. This means that the boundary layer on suction side is turbulent for almost the entire run of the airfoil. In some ways this is indicative of true flight conditions.

Finally, the effect of the simplification MSES employs on the e^n model was examined. The amplification magnitude for all of the instability waves was plotted for the flow over the NACA 23012 at a Reynolds number of 3×10^6 with $n = 13$ (matching the level of freestream turbulence found in the experiment) and $\alpha = 12$ deg (Fig. 4). As the figure shows, the transition was said to occur at $0.9\%c$, where the wave that MSES was tracking grew to more than 13 times its initial magnitude. However as the figure also shows, there are four other waves that have grown by more than the requisite 13 times indicating that transition should have occurred earlier on the airfoil according to the complete e^n model. This means that the laminar section of the boundary layer on the airfoils simulated might

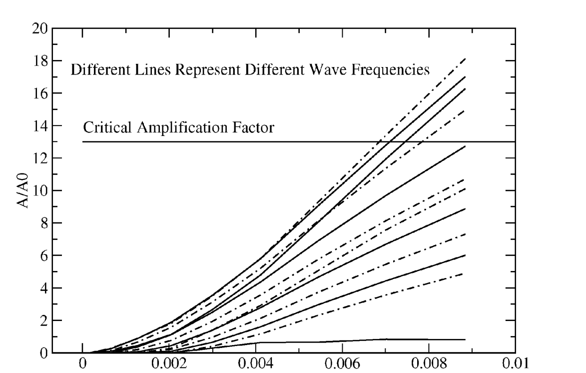


Fig. 4 Chordwise growth of Tollmien–Schlichting waves in boundary layer of NACA 23012.

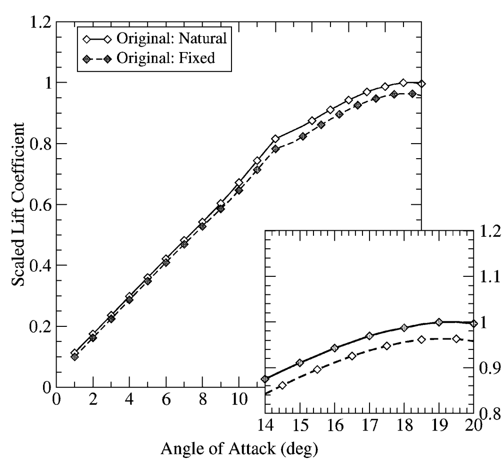
be longer than necessary giving a possible explanation why MSES consistently overpredicts the aerodynamic coefficients.

Cessna Caravan Airfoils

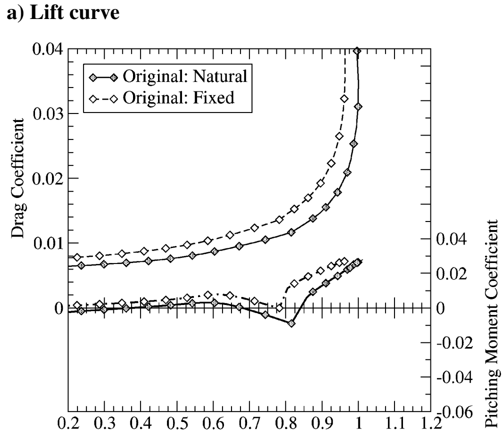
The original Caravan root and tip-wing sections were analyzed with MSES to determine the baseline performance of these airfoils for later comparison to the modified sections. Flight conditions at landing were those of interest as the aim of the AOG wing-modification project was to increase the lifting capacity of the Caravan. Aerodynamic performance of the airfoils is highlighted in this paper through the presentation of results for the airfoil undergoing natural transition ($n = 9$ or equivalently 0.07% turbulence intensity) and with a fully turbulent upper-surface boundary layer. As mentioned earlier, the fully turbulent case can be thought of as being more indicative of flight conditions; however, results of calculations using either fixed or natural transition are included in the presentation of results allowing for a comparison of these two models. This type of comparison can give an indication of the sensitivity of the boundary layer to such leading-edge contamination as insect debris or icing.

To approximate the flight conditions at landing, the freestream velocity was set to the Caravan stall speed of 75 kn (or equivalently 38.6 m/s or Mach 0.11 in standard air at sea level). This results in a Reynolds number (Re) at the root of 5.1×10^6 and at the tip of 3.2×10^6. The effect of the proximity of the ground was not included in the simulations performed in the current project. That is, all calculations were performed assuming the airfoil was in free air.

A plot of the variation of the scaled lift coefficient with angle of attack for the original Caravan root and tip airfoils can be found in Figs. 5a and 6a, respectively. The corresponding drag and pitching-moment polars for those airfoils are given in Figs. 5b and 6b. One feature to note in the lift curves is the presence of a kink in the curve

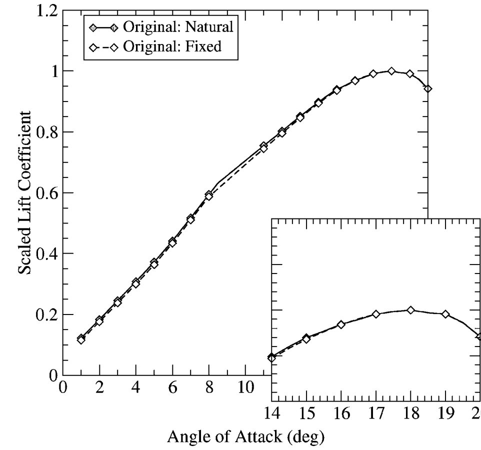


a) Lift curve

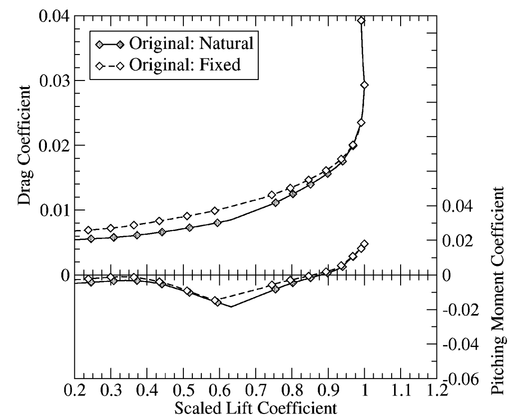


b) Drag and pitching-moment polars

Fig. 5 Aerodynamic performance of the original Caravan root airfoil: *Ma* = 0.11, and *Re* = 5.1 × 10⁶.



a) Lift curve



b) Drag and pitching-moment polars

Fig. 6 Aerodynamic performance of the original Caravan tip airfoil: *Ma* = 0.11, and *Re* = 3.2 × 10⁶.

at moderate angles of attack. This occurs when the pressure-side transition point reaches the trailing edge in cases where the flow undergoes natural transition or when that point retreats to the boundary-layer trip location in flows with fixed transition. This change from "unconstrained" to "constrained" flow causes the slight alteration in the aerodynamic characteristics of the airfoil. This phenomenon has also been documented by the developer of the code.[5] Also seen in the pitching-moment polar is an increase in nose-down C_m at moderate α. This behavior matches that seen in the experimental validation of the NACA 23012. As for the sensitivity of the aerodynamic coefficients to the different transition models, the tip airfoil shows little effect while the root section shows more. For both cases the longer run of laminar flow over the upper surface decreases the amount of drag produced and for the root airfoil allows slightly more lift to be generated. The chordwise distribution of the pressure field generating the lift is different between transition models, and this is reflected in the more nose-down pitching moment. To help highlight these observations, the surface-pressure distribution for these airfoils at 14-deg angle of attack is found in Figs. 7 and 8 for the root and tip airfoils, respectively.

AOG-Series Caravan Airfoils

The first modification to the leading edge was implemented in the AOG-series airfoils. The aerodynamic performance of these root wing and tip sections was analyzed at the same flight conditions ($Ma = 0.11$, free air) as the original wing simulations. The drooped leading-edge addition raised the Reynolds number of the airfoils slightly, although it is believed that this modest increase alone would have little effect on the performance of the airfoils.

The AOG-series root and wing-tip sections were simulated again assuming both free and fixed transition. The aerodynamic performance for the root airfoil, including a comparison to the original

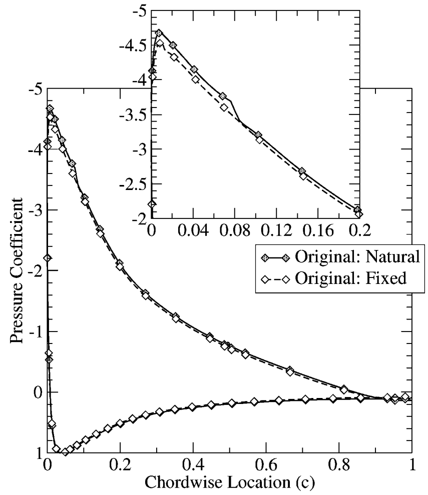


Fig. 7 Surface-pressure distribution on Caravan root airfoil: α = 14 deg.

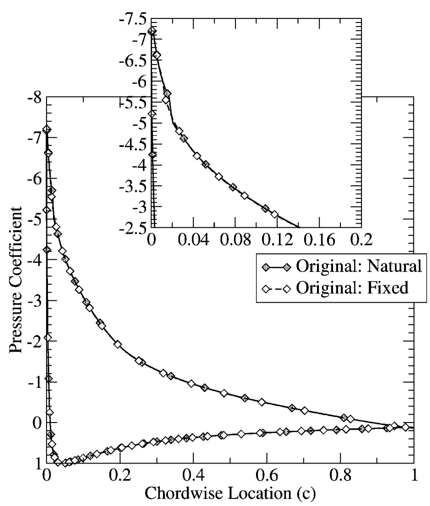
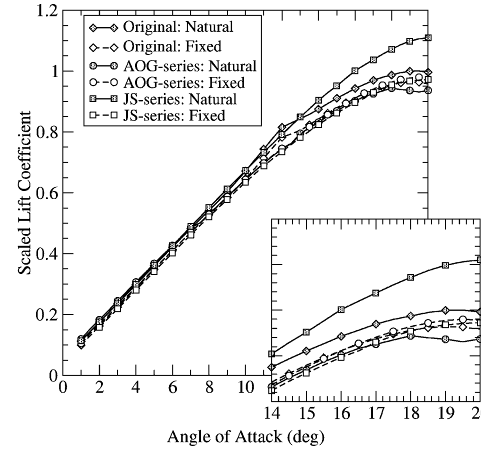
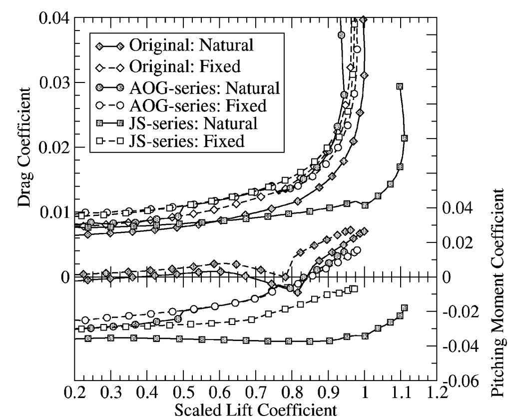


Fig. 8 Surface-pressure distribution on Caravan tip airfoil: $\alpha = 14$ deg.



a) Lift curve



b) Drag and pitching-moment polars

Fig. 9 Aerodynamic performance of the root-wing sections.

Caravan wing section, is found in Fig. 9 while the tip airfoil performance is found in Fig. 10. The aerodynamic coefficients presented in these figures have been nondimensionalized by the new chord length and then scaled by the appropriate $C_{l_{max}}$. The AOG-series root section shows a slight increase in $C_{l_{max}}$ with fixed transition and a decrease in maximum lift when the flow undergoes natural transition. As can be seen in the C_l vs α plot for the tip airfoil, the AOG-series airfoil shows a large variation in lift depending upon the type of transition. This is believed to be as a result of the high leading-edge curvature and the relatively long, relatively flat section on the upper surface of the airfoil just aft of the leading edge (Fig. 2b). This geometry also shows a slightly higher drag coefficient at low angles of attack yet less drag at higher α compared to the original Caravan section. However, what is more significant is the dramatic increase in nose-down pitching moment at low lift coefficients with the effect being slightly tempered at higher C_l (Figs. 9b and 10b). If this behavior is copied in the three-dimensional world of the wing and aircraft, then the flight characteristics of the modified aircraft could be significantly different than that of the original.

Plots of the C_P distribution for these airfoils are found in Fig. 11 for the AOG-series root airfoil and Fig. 12 for the tip. The surface-pressure distribution is very much affected by the local surface curvature, and this can be seen in the pressure plots. The AOG-series airfoils appear unable to maintain the deep suction on the upper surface especially under natural transition. This translates into a reduced amount of lift.

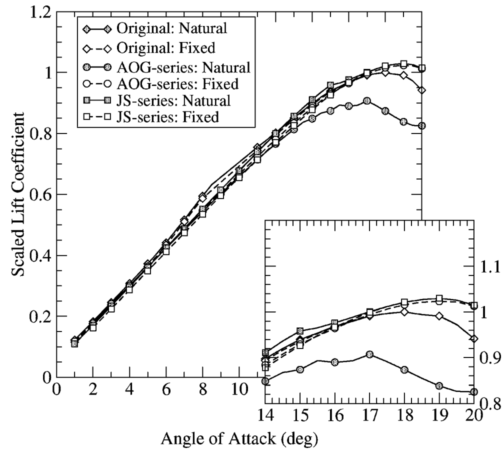
The results for the AOG-series airfoil sections show that they have the potential to accomplish the goal of increasing the lift of the wing. However, the tip airfoil does show a sensitivity to freestream turbulence (i.e., transition location). The increase in camber of the airfoils results in a significant change in pitching moment, which might be of concern for an aircraft outfitted with this wing modification.

JS-Series Airfoils

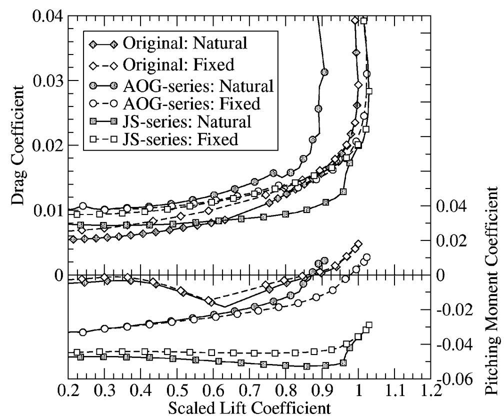
The second modification to the leading edge is found in the JS-series airfoils. These sections were analyzed at the landing conditions used to study the AOG-series airfoils (same Mach number and Reynolds number).

The aerodynamic coefficients of the JS-series airfoils, assuming flows with free and fixed transition, are found in Figs. 9 and 10 for the root and tip sections, respectively. The sensitivity of the airfoil to transition has moved to the root section from the tip for the JS-series airfoils; however, the mean performance of the JS root section is still above the original Caravan and AOG-series wing roots. The now insensitive tip airfoil shows a slight increase in maximum lift coefficient over the original Caravan tip. These two observations of $C_{l_{max}}$ indicate that the new airfoils when incorporated into a three-dimensional wing have the potential to increase the lifting capability of the aircraft (the overall aim of the wing modification project). As was seen in the pitching-moment polars of the AOG-series sections (Figs. 9b and 10b), the drooping of the leading edge increased the pitching moment of the airfoils, and that characteristic is much more dramatic for the JS-series sections. Again, this has ramifications on the handling and control aspects of an aircraft equipped with a wing based on these airfoils.

The surface-pressure distributions for the JS-series airfoils at $\alpha = 14$ deg can be found in Figs. 11 and 12. The curves for both the JS-series root (Fig. 11) and tip (Fig. 12) show that the airfoils generate their lift from a distribution, which is flatter and shifted more towards the trailing edge. It is this shifting rearward that manifests itself as an increase in nose-down pitching moment. The slight



a) Lift curve



b) Drag and pitching-moment polars

Fig. 10 Aerodynamic performance of the wing-tip sections: *Ma* = 0.11.

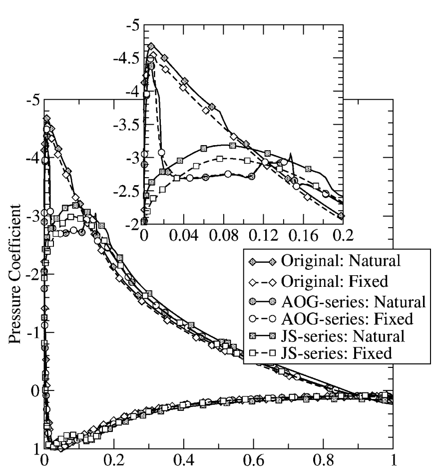


Fig. 11 Surface-pressure distribution on root airfoils: α = 14 deg.

increase in the surface pressure between 10%c and 20%c is a consequence of the slight mismatch in surface curvature between the new leading edge and the original airfoil section.

If one considers putting the JS-series airfoils on the wing of the Cessna Caravan, then the aircraft's performance will be significantly altered. Three aspects of the change in performance are highlighted here corresponding to three observations made in the two-dimensional calculations. The first is the increase in the lift coefficient at high α. This can be looked at in two different ways. If one looks at the lift of the wing written as $L = 1/2\rho V^2 C_L A$, then the roughly 7% increase in $C_{L_{\max}}$, combining the 11% increase at the root (Fig. 9) with the 3% increase at the tip (Fig. 10), means an increase in lifting capacity of the wing caused by changing the wing's shape. The wing's lift is further increased when the enhanced wing area caused by the leading-edge extension is taken into account. Alternatively, if one maintains the same overall lift requirement of the wing (i.e., same takeoff weight of the aircraft) then the necessary takeoff speed will be reduced by 3.4% again as a result of the wing shape changes. Furthermore, that lift will be produced at a lower angle of attack because of the nose-down tilt of the mean chord line of the JS-series airfoil sections when installed on the wing. The momentum balance of the aircraft will be altered because of a shifting of the aerodynamic center of the wing.

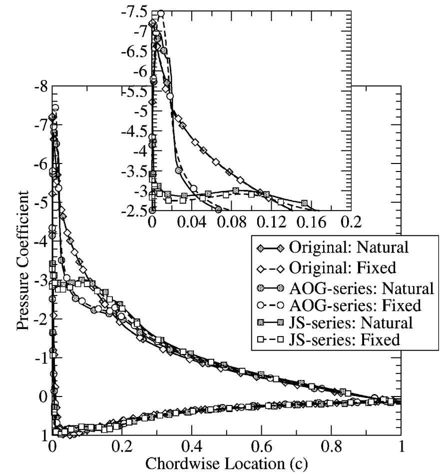


Fig. 12 Surface-pressure distribution on tip airfoils: α = 14 deg.

The second area highlighted by the two-dimensional calculations is the drastic increase in nose-down pitching moment of the JS-series airfoils caused by the increase camber. The CFD results show an average increase in C_m of roughly -0.45 across the wing. If this change in pitching moment is counterbalanced by the lift of the tail, then that would require an increase in the required downward tail lift of 0.05 (based on the dimensions of the Caravan[4]) or roughly 0.5 deg. This increase in tail loading must be addressed when considering the overall stability and control of the aircraft with the leading-edge modifications.

The final observation of the two-dimensional results to be considered here in terms of its effect on the full aircraft performance is the shape of the surface-pressure distribution. With the removal of the deep suction peak, the stalling characteristics of the tip section could be drastically altered from a leading-edge to trailing-edge stall. This could reduce or eliminate the abrupt stall currently experienced by the Caravan. Further study of the airfoils with an accurate capture of the leading-edge stall of the NACA 23012 would provide further insight. The modified pressure distribution also has implications for the susceptibility of the wing to icing. The presence of a shallower suction peak could improve the performance of the wing in iced conditions as the presence of small amounts of ice is less likely to drastically alter the suction peak (and thus the lift) of the wing section. It is known that the Caravan has been involved in several icing-related incidents over the past decades.[10] Further testing of the airfoil sections or the wing in icing conditions would confirm or refute this hypothesis.

Cruise Conditions

The design of airfoils based on their takeoff/landing performance provides insight into the potential increase in lifting capability of an aircraft with a wing based on these profiles. However, landing is only one portion of the flight envelope, and any increase in C_l for that flight condition must not come at the price of performance penalties in other regions, in particular at cruise. To this end, the six airfoils studied in the preceding sections were analyzed at flight Mach and Reynolds numbers. A typical cruising speed for the Cessna Caravan is 200 mph (89.4 m/s), which under standard atmosphere at 10,000 ft (3048 m) translates to a freestream Mach number of 0.27 and a three-fold increase in Reynolds number.

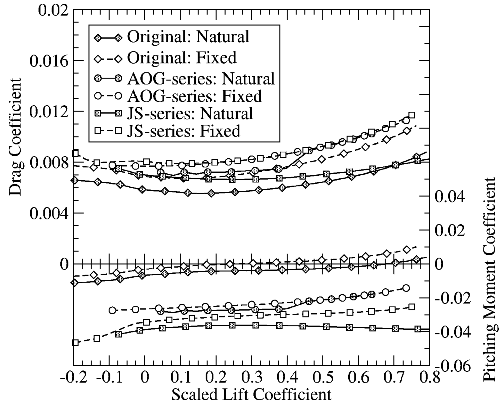


Fig. 13 Aerodynamic performance of root-wing sections at cruise.

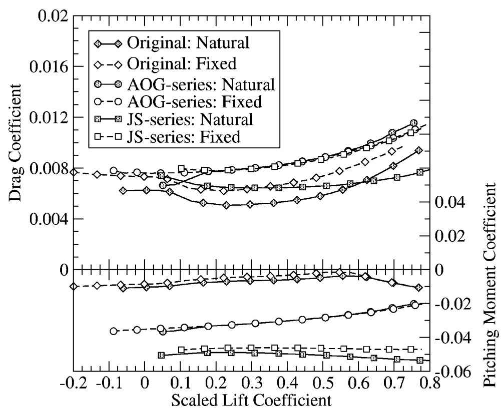


Fig. 14 Aerodynamic performance of tip-wing sections at cruise.

Similar to previous calculations, the aerodynamic coefficients were computed for each airfoil assuming free and fixed transition. A summary of the various drag and pitching-moment polars can be found in Figs. 13 and 14 for the collection of root and tip airfoils, respectively. Several observations can be made from these figures. First, at these flight conditions the pitching-moment coefficients for all of the airfoils is relatively insensitive to the type of transition present in the calculation. In terms of the drag of the new airfoils, they show only a modest increase at low lift coefficients with even less difference (and in some cases less drag) at higher C_l. The drag of the original and JS-series sections does show a slight variation depending upon type of transition modeled. As was seen in the results for the drooped leading-edge airfoils at landing conditions, there continues to be a significant nose-down pitching moment accompanying the increase in camber.

Conclusions

The addition of a leading-edge extension, which droops the leading edge of a general aviation aircraft wing, akin to a deployed slat, increases the camber of the wing and thus has the potential to increase its lifting capability during takeoff. The study examined the original Cessna Caravan wing-root and tip-wing sections as well as two proposed modifications to those sections to determine their respective aerodynamic performances. The tool of choice for these analyses was MSES, an Euler/coupled boundary-layer code that includes transition modeling capabilities.

As a validation exercise, MSES was applied to the calculation of the aerodynamic coefficients of the Cessna wing-tip section, and the results were compared against historical experimental data. Although MSES overpredicted the value of various aerodynamic coefficients, the relative performance of the airfoils was captured well. This exercise provided confidence in the ability to compare the relative performance of the various airfoils in the study using results computed by MSES.

MSES uses a simplified e^n model to predict transition, and in the exploration of the effects of this numerical algorithm it was discovered that the overprediction of the lift coefficient might be explained by a delay in the location of transition predicted by the method. With this observation in mind, each airfoil was analyzed assuming that the upper surface underwent transition at a location determined by the model (i.e., natural) or at $1\%c$ (i.e., fixed).

From the results presented, it can be seen that drooping the leading edge has the potential to increase the maximum lift of the root and tip-wing sections. However, it is also possible to increase the sensitivity of the airfoils to freestream turbulence by this modification. The possible increase in lift comes with a modest increase in drag at cruise, but in both flight conditions studied (landing and cruise) the increase in camber of the airfoil was accompanied by a dramatic increase in nose-down pitching moment.

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