Lift Optimization Study of a Multi-Element Three-Segment Variable Camber Airfoil

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This paper reports a detailed computational high-lift study of the Variable Camber Continuous Trailing Edge Flap (VCCTEF) system carried out to explore the best VCCTEF designs, in conjunction with a leading edge flap called the Variable Camber Krueger (VCK), for take-off and landing. For this purpose, a three-segment variable camber airfoil employed as a performance adaptive aeroelastic wing shaping control effector for a NASA Generic Transport Model (GTM) in landing and take-off configurations is considered. The objective of the study is to define optimal high-lift VCCTEF settings and VCK settings/configurations. A total of 224 combinations of VCK settings/configurations and VCCTEF settings are considered for the inboard GTM wing, where the VCCTEFs are configured as a Fowler flap that forms a slot between the VCCTEF and the main wing. For the VCK settings of deflection angles of 55°, 60° and 65°, 18, 19 and 19 vck configurations, respectively, were considered for each of the 4 different VCCTEF deflection settings. Different vck configurations were defined by varying the horizontal and vertical distance of the vck from the main wing. A computational investigation using a Reynolds-Averaged Navier-Stokes (RANS) solver was carried out to complement a wind-tunnel experimental study covering three of these configurations with the goal of identifying the most optimal high-lift configurations. Four most optimal high-lift configurations, corresponding to each of the VCK deflection settings, have been identified out of all the different configurations considered in this study yielding the highest lift performance.

Keywords: Variable Camber Continuous Trailing Edge Flap (VCCTEF), Drag Optimization, Generic Transport Model.

Nomenclature

$\alpha$ = angle of attack (AoA)
$C_l$ = lift coefficient (total or sectional)
$C_d$ = drag coefficient (total or sectional)
$C_p$ = pressure coefficient: $2(p - p_\infty) / \rho V_\infty^2$
$M$ = Mach number
$Re$ = Reynolds number
$M_\infty$ = free stream Mach number
$V_\infty$ = free stream Velocity
VCK = Variable Camber Krueger, a high lift leading edge flap
VCCTEF = Variable Camber Continuous Trailing Edge
vck = refers to variable camber Krueger configurations
$x$ = horizontal offset
$y$ = vertical offset

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1 Introduction

The Advanced Air Transportation Technologies (AATT) project is conducting multidisciplinary foundational research to investigate advanced concepts and technologies for future aircraft systems under the Advanced Air Vehicle Program (AAVP) of the NASA Aeronautics Research Mission Directorate. A NASA study entitled "Elastically Shaped Future Air Vehicle Concept" was conducted in 2010\textsuperscript{1,2} to examine new concepts that can enable active control of wing aeroelasticity to achieve drag reduction. This study showed that highly flexible wing aerodynamic surfaces can be elastically shaped in-flight by active control of wing twist and vertical deflection in order to optimize the local angle of attack of wing sections. Thus aerodynamic efficiency can be improved through drag reduction during cruise and enhanced lift performance during take-off and landing.

The study shows that active aeroelastic wing shaping control can have a potential drag reduction benefit. Conventional flap and slat devices inherently generate drag as they increase lift. The study shows that in cruise, conventional flap and slat systems are not aerodynamically efficient for use in active aeroelastic wing shaping control for drag reduction. A new flap concept, referred to as Variable Camber Continuous Trailing Edge Flap (VCCTEF) system, was conceived by NASA to address this need.\textsuperscript{1}

Initial study results indicate that the VCCTEF system may offer a potential pay-off in drag reduction in cruise that could provide significant fuel savings. Fig. 1 illustrates the VCCTEF deployed on the NASA generic transport model (GTM).

NASA and Boeing are currently conducting further studies of the VCCTEF under the research element Performance Adaptive Aeroelastic Wing (PAAW) within the AATT project.\textsuperscript{3,4} This study built upon the development of the VCCTEF system (shown in Fig. 2) for the GTM\textsuperscript{5} employs light-weight shaped memory alloy (SMA) technology for actuation and three separate chordwise flap segments shaped to provide a variable camber to the flap. Introduction of this camber has potential for drag reduction as compared to a conventional straight, plain flap. The flap is also made up of individual 2-foot spanwise sections, which enable different flap settings at each flap spanwise position. This enables wing twist shape control as a function of span to establish the best lift-to-drag ratio ($L/D$) at any aircraft gross weight or mission segment. Current wing twist on commercial transports is permanently set for one cruise, which is usually a 50\% fuel loading or mid-point on the gross weight schedule. The VCCTEF offers different wing twist settings for each gross weight condition and also different settings for climb, cruise and descent, which is a major factor in obtaining the best $L/D$ for all gross weight conditions and phases of flight. The second feature of VCCTEF is a continuous trailing edge. The individual 2-foot spanwise flap sections are connected with a flexible covering, so no breaks can occur in the flap platform, thus reducing excessive vorticity generation. This can reduce drag and airframe noise. Variable camber when combined with the continuous trailing edge results in a further reduction in drag.

In summary, it can also offer a potential noise reduction benefit due to distinct optimal settings for climb, cruise and descent. In a previous paper,\textsuperscript{6} a computational study was conducted to explore the two-dimensional viscous effects in cruise of a number of VCCTEF configurations on lift and drag of the GTM wing section at the wing planform break. The flow solver OVERFLOW was used to conduct this study. The results identified the most aerodynamically efficient VCCTEF configuration among the initial candidates. The study also showed that a three-segment variable camber flap is aerodynamically more efficient than a single-element plain flap. A recent high-lift wind tunnel test conducted in July 2014 at University of Washington Aeronautical Laboratory\textsuperscript{7,8} confirms this observation.

The present study explores the high-lift design space for the tri-element airfoil typical of a GTM wing section. The tri-element airfoil is comprised of VCK, main airfoil and the VCCTEF. The design space consists of 224 configurations drawn from various combinations of of VCK and VCCTEF settings, as described in the next section. Limited experimental data\textsuperscript{7−10} are available corresponding to four configurations (VCK65, VCK60, VCK55, VCK50 – vck1), out of the 224 considered here computationally. In the following paragraphs, details of the computational methodology and computational grids used will be presented. In the high-lift flight configuration, we want to minimize the stall speed, which can be accomplished by maximizing $C_l$, and the results will be presented below in that context.
2 Methodology

The Reynolds-Averaged Navier-Stokes (RANS) solver, OVERFLOW, with the Spalart-Allmaras (SA) turbulence model\(^9\) has been used for the current computational study. Grids were generated using the NASA Chimera Grid Tools (CGT).

Numerous combinations corresponding to 18 \(vck\) configurations for VCK setting (deflection angle) of 55° and 19 \(vck\) configurations each for VCK settings of 60° and 65° with respect to the main wing, and 4 VCCTEF settings with the Fowler slot for the inboard wing are considered in this study. These \(vck\) configurations along with the 4 VCCTEF settings are represented in Table 1 below. Three VCK settings are considered, corresponding to deflection angles of 55°, 60° and 65°. For each VCK setting, VCK55, VCK60 and VCK65, the \(vck\) configurations in terms of \(x\) and \(y\) displacement offset with respect to one experimental configuration (VCK65 + \(vck\)1) studied experimentally are shown in Fig. 3, Fig. 4 and Fig. 5, respectively. Nineteen \(vck\) configurations are designated \(vck\)1, \(vck\)2, \(vck\)3, ... , \(vck\)18, \(vck\)19. Detailed computational results discussing the lift characteristics will be shown below for all the 224 configurations to explore better design than the four studied experimentally.

### Table 1: Definition of \(vck\)-VCCTEF Configurations

<table>
<thead>
<tr>
<th>(vck) Configuration</th>
<th>(10/10/10)</th>
<th>(15/10/5)</th>
<th>(20/5/5)</th>
<th>(30/0/0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(vck)1</td>
<td>(vck)1 + (10/10/10)</td>
<td>(vck)1 + (15/10/5)</td>
<td>(vck)1 + (20/5/5)</td>
<td>(vck)1 + (30/0/0)</td>
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<td>(vck)2 + (10/10/10)</td>
<td>(vck)2 + (15/10/5)</td>
<td>(vck)2 + (20/5/5)</td>
<td>(vck)2 + (30/0/0)</td>
</tr>
<tr>
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<td>(vck)3 + (10/10/10)</td>
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<td>(vck)4 + (30/0/0)</td>
</tr>
<tr>
<td>(vck)5</td>
<td>(vck)5 + (10/10/10)</td>
<td>(vck)5 + (15/10/5)</td>
<td>(vck)5 + (20/5/5)</td>
<td>(vck)5 + (30/0/0)</td>
</tr>
<tr>
<td>(vck)19</td>
<td>(vck)19 + (10/10/10)</td>
<td>(vck)19 + (15/10/5)</td>
<td>(vck)19 + (20/5/5)</td>
<td>(vck)19 + (30/0/0)</td>
</tr>
</tbody>
</table>

\(vck\) configurations are represented in Fig. 4, Fig. 5 and Fig. 6

### Table 2: Definition of VCCTEF Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Notation</th>
<th>Flap 1, deg</th>
<th>Flap 2, deg</th>
<th>Flap 3, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-segment circular arc camber</td>
<td>10/10/10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>3-segment semi-rigid arc camber</td>
<td>15/10/5</td>
<td>15</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>3-segment</td>
<td>20/5/5</td>
<td>20</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>1-segment rigid flap</td>
<td>30/0/0</td>
<td>30</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Flap deflection angles are relative to the upstream segments

Fig. 6 shows the four VCCTEF settings, corresponding to 4 different flap deflection angles, as shown in Table 2. Definition of various configurations are listed in Table 1. The four VCCTEF settings are denoted by 10/10/10, 15/10/5, 20/5/5 and 30/0/0.

3 Grid Sensitivity and Results

A grid sensitivity study using seven different grid levels was carried out with one configuration, VCK65/\(vck\)1 + VCCTEF-30/0/0, which corresponds to Fig. 5(a) and Fig. 6, where 30/0/0 is labeled 30 in Fig. 6. The grid resolution for the seven grids is shown in Table 3. First, the grid level 3 corresponding to the \(vck\)1 + 30/0/0 configuration is shown in Figs. 7(a,b,c) as a representative grid.

Fig. 8 shows the \(C_l\) vs \(\alpha\) grid sensitivity results corresponding to the seven grids mentioned above. Results corresponding to grid levels 1, 2 and 3 shown in red, green and blue respectively, are appreciably different from the grid level 4, 5, 6 and 7 results, shown in magenta, cyan, black and black symbols, respectively.
But, results corresponding to grid levels 4, 5, 6 and 7 are practically the same. In the post-stall region any discrepancy among the various grid levels is ignored, since there are unsteady RANS effects that are not adequately resolved. So, in the rest of the paper, results shown will correspond to the grid level 4.

A total of $4\times(19\times2+18\times1) = 224$ cases ($19$ vck configurations for each of the two VCK settings, VCK65 and VCK60, $18$ vck configurations for the VCCTEF setting, all corresponding to 4 different VCCTEF settings) are considered. A sweep of angle of attack ranging from -5 deg to 20 deg is considered. There are only $18$ vck configurations in the case of VCK55, since the 19th configuration is unrealistic for this case. For all of the cases considered, grid level 4 was used for comparison of results, which are discussed below.

Instead of showing the results for all the 224 cases individually, a 2D bar graph is first presented showing $C_{l_{max}}$ for the VCCTEF-10x10x10 setting in Fig. 9. Corresponding plot for $C_{d_{max}}$ is shown in Fig. 10. Fig. 9 gives an overall view of the lift performance of the VCCTEF-10x10x10 setting for all the vck configurations corresponding to VCK55 and VCK60 and VCK65, and Fig. 10 shows corresponding results for $C_{d_{max}}$. Similarly, Fig. 11 and Fig. 12 show $C_{l_{max}}$ and $C_{d_{max}}$, respectively, for the VCCTEF-15x10x5 setting. Fig. 13 and Fig. 14 show the corresponding results for the VCCTEF-20x5x5 setting, and Fig. 15 and Fig. 16 show the corresponding results for the VCCTEF-30x0x0 setting. Figs. 9 through 16 give an overall view of the $C_{l_{max}}$ and $C_{d_{max}}$ results for all the cases considered. The details of why these vck configurations yield distinctly different lift characteristics will be presented in a separate paper, where the corresponding flow fields will be studied in detail. The present paper is focused on the design aspects of the problem.

Results for $C_l$ vs $\alpha$ are shown for a subset of these 224 cases. For this purpose, cases giving 4 largest values of $C_{l_{max}}$ are selected from Fig. 9 through Fig. 16. It turns out that for VCK55 setting, vck configurations of 2, 4, 14 and 15 give the largest $C_{l_{max}}$ for all the four VCCTEF settings of 10x10x10, 15x10x5, 20x5x5 and 30x0x0, and for VCK60 and VCK65 settings, vck configurations of 2, 7, 15 and 19 give the largest $C_{l_{max}}$ for all the four VCCTEF settings. Therefore, in the discussion of results below, only these vck configurations will be considered.

Before discussing the lift curves corresponding to these selected vck configurations, a test case corresponding to the VCCTEF setting of 30x0x0 and vck1 configuration was investigated for the $\alpha$ range of -5,-4,-3,-2,-1,0,5,10,11,12,13,...,20. Fig. 17a and Fig. 17b show the $C_l$ vs $\alpha$ and drag polar results, respectively. It is observed that a constant lift curve slope exists only beyond $\alpha = 0$, which shows that at lower angles of attack, the lift curve for the tri-element VCK-wing-VCCTEF system does not follow linear theory. This is shown by a nonlinear lift curve in the $\alpha$ range below 0 deg. In discussing the lift curve and drag polar results below, the $\alpha$ range of -5,0,5,10,11,12,13,...,20 was considered.

Fig. 18(a,b) shows the $C_l$ vs $\alpha$ and drag polar results, respectively, for the VCK55 and VCCTEF-10x10x10 settings corresponding to vck2, vck4, vck14 and vck15 configurations. The vck15 case consistently outperforms the other three, based on maximum $C_l$. As mentioned above, in high-lift flight configuration, we want to minimize the stall speed, which can be accomplished by maximizing $C_l$. The vck15 case also performs the best for the other three VCCTEF settings, 15x10x5, 20x5x5 and 30x0x0 for the VCK55 setting, as shown in Fig. 19(a,b), Fig. 20(a,b) and Fig. 21(a,b), respectively.

The situation is different for the VCK60 setting, where the best lift performance ($C_{l_{max}}$ is demonstrated by the vck2 case for all the VCCTEF settings. This is shown in Fig. 22 through Fig. 25. For the VCK65 setting, best lift performance is demonstrated again by the vck15 case for all the VCCTEF settings, as shown in Fig. 26 through Fig. 29.

For the case of VCK55 setting, corresponding to the four best vck configurations, i.e., vck2, vck4, vck14

Table 3: Grid Sensitivity: Grid Resolution of Six Different Grids

<table>
<thead>
<tr>
<th>Grid Level</th>
<th>VCK</th>
<th>Main Wing</th>
<th>VCCTEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>210x87x3</td>
<td>311x87x3</td>
<td>233x87x3</td>
</tr>
<tr>
<td>2</td>
<td>258x96x3</td>
<td>475x96x3</td>
<td>271x96x3</td>
</tr>
<tr>
<td>3</td>
<td>263x106x3</td>
<td>522x106x3</td>
<td>290x106x3</td>
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<tr>
<td>4</td>
<td>436x106x3</td>
<td>694x106x3</td>
<td>471x106x3</td>
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<tr>
<td>5</td>
<td>639x106x3</td>
<td>694x106x3</td>
<td>471x106x3</td>
</tr>
<tr>
<td>6</td>
<td>639x114x3</td>
<td>694x106x3</td>
<td>471x106x3</td>
</tr>
<tr>
<td>7</td>
<td>639x114x3</td>
<td>837x114x3</td>
<td>625x114x3</td>
</tr>
</tbody>
</table>
and vck15, various $C_p$ plots are discussed below. Fig. 30(a), Fig. 30(b) and Fig. 30(c) show pressure distributions over the individual three elements of the tri-element airfoil, VCK, main wing and VCCTEF-20x5x5, respectively, each corresponding to the vck2, vck4, vck14 and vck15 configurations. Fig. 31(a), Fig. 31(b), Fig. 31(c) and Fig. 31(d) show consolidated pressure distributions over the tri-element system with the vck2, vck4, vck14 and vck15 configurations, respectively. The consolidated $C_p$ plots show a direct comparison among the three elements of the tri-element airfoil on the same scale.

Fig. 31 shows the highest $C_p$ corresponding to vck2 and next highest $C_p$ for the vck14 configuration for the VCK flap; highest $C_p$ corresponding to vck4 and next highest $C_p$ for the vck15 configuration for the main wing; practically the same $C_p$ for all the four vck configurations for the VCCTEF (20x5x5), with vck15 slightly outperforming the other three vck configurations. The overall result of this is shown in Fig. 20(a), where vck15 configuration yields the best high lift performance, followed by vck2 with the next best high lift performance. The inspection of $C_p$ profiles is important since it is directly correlated to $C_l$.

Similarly, Fig. 32(a), Fig. 32(b) and Fig. 32(c) show pressure distributions over the three individual airfoil elements corresponding to the VCK60 setting and the VCCTEF-20x5x5 setting. Fig. 33(a), Fig. 33(b), Fig. 33(c) and Fig. 33(d) show consolidated pressure distributions over the tri-element corresponding to the four vck configurations, vck2, vck7, vck15 and vck19, as mentioned above. Fig. 32 shows the highest $C_p$ corresponding to vck2 and next highest $C_p$ for the vck15 configuration for the VCK flap; highest $C_p$ corresponding to vck15 and next highest $C_p$ for the vck19 configuration for the main wing; highest and the next highest $C_p$ for vck2 and vck15, respectively, for the VCCTEF (20x5x5). The overall result of this is shown in Fig. 24(a), where vck2 and vck15 configurations yields the best and the next best high lift performance.

Fig. 34(a-c) and Fig. 35(a-d) show corresponding results for the VCK65 setting. Fig. 34 shows the highest $C_p$ corresponding to vck15 and next highest $C_p$ for the vck2 configuration for the VCK flap; highest $C_p$ corresponding to vck15 and next highest $C_p$ for the vck2 configuration for the main wing; highest and the next highest $C_p$ for vck15 and vck2, respectively, for the VCCTEF (20x5x5). The overall result of this is shown in Fig. 28(a), where vck15 and vck2 configurations yields the best and the next best high lift performance. For the case of VCK65, all the three elements of the tri-element airfoil behave similarly, in terms of $C_p$ distributions.

It is shown that vck15 and vck2 configurations are the top two candidates, in terms of overall high lift performance, out of all the three VCK settings (VCK55, VCK60 and VCK65) for the VCCTEF-20x5x5 setting. Fig. 29(a) further shows that the VCCTEF-30x0x0 setting gives the highest lift performance ($C_l - \alpha$) corresponding to vck15 and vck2 configurations out of all the 4 VCCTEF settings.

4 Summary

In the present study, we explored, using RANS calculations, various design configurations of the three-element GTM airfoil, consisting of 19 vck configurations corresponding to each of the two VCK settings (VCK00 and VCK65), and 18 vck configurations corresponding to the VCK55 setting and 4 VCCTEF settings with the Fowler slot on the inboard section of the wing. We have identified two topmost vck configurations corresponding to each of the three VCK settings. For all the VCK settings, vck2 and vck15 give the best lift performance, regardless of the four VCCTEF settings used. In particular, the VCCTEF-30x0x0 setting gives the highest overall lift performance with the vck2 and vck15 configurations. Thus, the best configurations for the GTM airfoil have been identified out of all the 224 cases studied. This provides a useful guide for the wind-tunnel experiment to verify the best design GTM configurations. Some of these best high-lift configurations offer a counter-intuitive design that would not have been considered experimentally a priori.

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NNL12AD09T entitled "Development of Variable Camber Continuous Trailing Edge Flap System for B757 Configured with a More Flexible Wing."

6 References


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