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Active Flow Control Using High-Frequency Compliant Structures

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Flow control to avoid or delay boundary-layer separation on a wing can dramatically improve the performance of most air vehicles in strategic parts of their individual flight envelopes. Previous aerodynamic experiments and computations have indicated that unsteady excitation at the appropriate frequency can delay boundary-layer separation and wing stall more effectively than steady flow perturbations and that these unsteady perturbations, when generated in an optimum frequency range, maximize the extent of flow separation control for specific flight conditions. Preliminary aerodynamic experiments have been performed on a deflected trailing-edge flap to evaluate turbulent boundary layer separation control with a deployable high-frequency micro-vortex-generator (HiMVG) array. The HiMVG design tested incorporated emerging displacement amplification compliant structures technology that deployed micro-vortex-generator blades 5 mm, through a range of frequencies between 30 and 70 Hz, when driven by an appropriately sized voice–coil actuator. The mechanical HiMVG system tested produced an oscillatory stream of boundary-layer embedded vortices that proved effective in mitigating flow separation on the upper surface of a deflected flap when a similar array of static vortex generators could not. A second-generation HiMVG design driven by a piezoelectric actuator was also conceptualized. Candidate flow control applications for this second-generation design are discussed.

Nomenclature

C_p	=	pressure coefficient, $(p - p_\infty)/\frac{1}{2}\rho U_\infty^2$
c	=	length of model (37 in.)
f	=	unsteady flow disturbance frequency
F^+	=	reduced frequency (nondimensional), $(f \cdot X_{\mathrm{te}})/U_\infty$
H_{MVG}	=	design height of microvortex generator
U_∞	=	freestream velocity
x	=	distance from model leading edge
X_{te}	=	distance from actuator position to trailing edge of flap
δ	=	boundary layer height

Introduction

FLOW separation control using unsteady perturbations is not entirely new; in fact, there have been several recently funded projects in this area[1–3] addressing pneumatic concepts that have produced some rather exciting results. For example, the pulsed vortex generator jet work, initiated by McManus et al.,[2] is proceeding on two fronts, one studying dynamic stall improvement[4] and the another focused on reducing shock-induced separation on transonic airfoils.[5] The thrust of the work reported in this paper, on the other hand, details the initial development and testing of an unsteady flow control device that is an electrically operated mechanical design. The overarching project goal has been the development and demonstration of an oscillatory flow control device that performs the flow control function as well as the best pneumatic systems. However, because of design simplicity, this type of device may be easier to integrate, particularly for transonic flow control applications where the mass flow requirements of pneumatic systems can be significant.

The flow control mechanism of the referenced pneumatic systems is to generate periodic vortices in a separating flow at or near an optimal frequency. Vortices formed at this frequency exhibit high streamwise momentum and are driven toward the surface energizing the boundary layer thus eliminating massive separation. Whereas the pneumatic systems produce their unsteady flow excitation by injecting air in an oscillatory manner, the high-frequency micro-vortex-generator (HiMVG) device presented here produces its unsteady flowfield by moving a mechanical element (in this case a micro vortex generator) at the optimum frequency for the flow conditions involved. The present use of compliant structures is quite different than past flow control devices using this nomenclature, such as compliant wall surfaces,[6] which interact with the boundary layer actively or passively, or microflaps, which interact directly with the flowfield. The mechanical system shown in Fig. 1 uses a 20:1 displacement amplification compliant structures device designed at FlexSys, Inc., that, when driven by an actuator with the proper characteristics, can deploy a blade vortex array to the height required for effective vortex formation. In Fig. 1, the motion blurs the vortex generator blades and the cover plate is removed to expose the inner working of the displacement amplification devices.

The aerodynamic device used to produce the oscillatory flowfield, the micro vortex generator, was configured according to the design parameters developed by Lin[7] in his benchmark research on vortex generator size optimization for turbulent boundary-layer separation control. A previous attempt at using deployable vortex generators for boundary-layer separation control[8] had system design constraints that thus far has limited deployment frequency to the 10–20 Hz range. This system performed the separation control function as well as a static vortex generator array, but operated at a reduced frequency well below that needed for optimum separation control based

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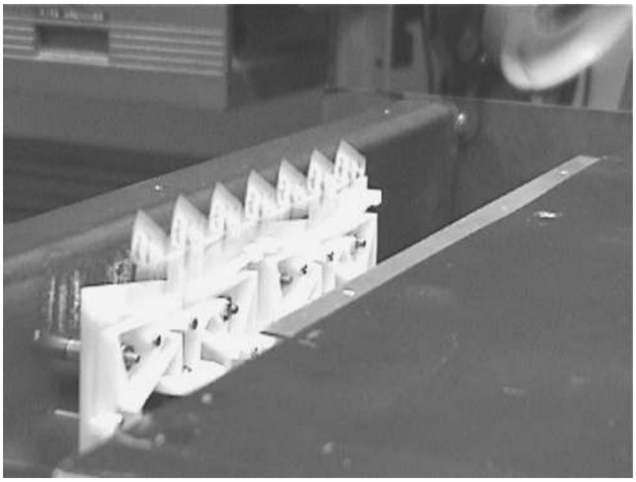


Fig. 1 Deployable HiMVG system installed and operating at 90 Hz.

on previous experimental evidence.[3] A properly designed displacement amplification compliant structure, coupled with an appropriate actuator, eliminates this vortex-generator deployment frequency constraint. Compliant structure technology permits the design of a mechanical system that can generate an oscillatory flowfield at the reduced frequency needed for best separation control performance. The term high frequency is used here to differentiate the present devices from previous methods of deploying vane vortex generators into the flowfield that have been limited to much lower frequencies. Whereas there are other methods of oscillatory forcing being investigated at similar or even higher frequencies,[6] the present method promises the ability to provide both high-frequency and large-amplitude disturbances for separation control regardless of the flight environment.

Boundary-Layer Separation Control

Many boundary-layer separation control concepts have been studied and developed to varying degrees in previous research efforts. Several of the more recent dynamic flow control concepts that are pertinent to this research activity will be discussed in some detail. However, first, details of a static flow control concept with relevance to this project will be reviewed.

The vortex generator, or to be more specific in its relationship to this dynamic flow control project, the micro vortex generator, a compact version of the larger boundary-layer height (δ-scale) vortex generator developed and patented by Taylor of United Aircraft Corporation, dates back to 1947. Lin's recent research[7] on reducing the size of vortex generators, while still retaining their boundary-layer control performance, led to the development of what he called a micro vortex generator (MVG), with a blade height of from 0.2 to 0.4 times the boundary-layer thickness. Perhaps a more precise name for these devices would be mini vortex generator because, although the properly sized devices are smaller than traditional vane-style vortex generators (VGs), they are seldom in the micromillimeter range. In any case, these MVGs proved just as effective in preventing the separation of a turbulent boundary layer as the larger δ-scale VGs with a considerable reduction in total system drag. Whereas drag is not a critical issue with deployable VGs, which are only inserted into the flow when required, the need to rapidly deploy the devices at the high frequencies required to produce good dynamic flow control results requires a small, lightweight VG blade. Therefore, the Lin optimized blade shapes are compatible with the HiMVG design philosophy.

VGs work by increasing the mixing between high-energy air in the outer regions of the boundary layer with the low-energy air near the surface. This mixing is accomplished by an appropriately sized and oriented blade located on the aerodynamic surface. VG blades in effect produce a coherent helical vortex structure that moves high-momentum air toward the surface energizing the low-energy air. An excellent account of this boundary-layer mixing process is given, in the classic paper by Schubauer and Spangenberg.[9] Of particular interest to the current research activity is that properly designed VGs produce strong, coherent vortex structures that trail downstream. In the dynamic flow control concepts to be discussed next, this factor becomes an important parameter with regard to system performance.

The two active flow control concepts that form the basis for the HiMVG research of this project are the pulsed VG jet (PVGJ) concept of McManus et al.[2] and periodic excitation control studies of Wygnanski[10] and Seifert et al.[11] Although the exact mechanism of flow control by unsteady excitation is not fully understood, both of the referenced concepts involve the formation of vortices in a separating flow. If this periodic formation of vortices occurs at or near an optimum frequency, the transfer of energy from the outer region to the inner region of the boundary layer is maximized. For these two concepts, air is the working medium that produces the unsteady excitation. The concept of this research effort, on the other hand, produces the unsteady excitation by appropriate motion of a mechanical element, a deployable MVG.

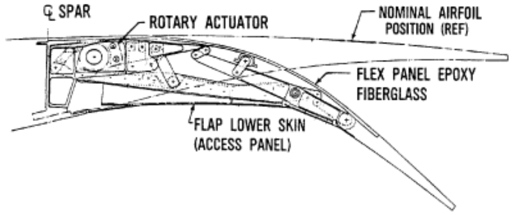
First, background on the PVGJ system developed by McManus et al.[2] is presented. This system uses a jet, pulsing at the correct frequency, to produce a high-energy vortex structure tuned to the boundary-layer shedding frequency. The PVGJ system can readily adjust three parameters, the pulsing frequency, the jet velocity ratio, and the duty cycle, to produce the coherent structures that maximize energy addition into the boundary layer preventing separation. In this research,[12] Magill and McManus have demonstrated the separation control potential of the PVGJ concept in a subsonic flow environment to be significant. The maximum lift coefficient of a NACA-4412 airfoil with a simple leading-edge flap was increased more than 20% by PVGJs, but this large increment was degraded if the pulsing frequency and amplitude were not properly tuned. The mass flow rate required to effect this performance improvement is low for subsonic flow conditions. However, in a transonic flow environment, the mass flow required to produce coherent vortex structures can become significant.[5] This factor plus integration difficulties have been the major deterrents limiting PVGJ applications.

A series of flow control (described in Wygnanski[10]) has demonstrated flow control results similar to McManus's[2] work using a different excitation process. Wygnanski[10] used a low steady blowing configuration with oscillatory blowing at the correct frequency to modulate the formation of vortices. Both McManus[2] and Wygnanski[10] use a Strouhal-number-based relationship to develop an empirical expression for optimum flow attachment. In this paper, the Wygnanski[10] form of the empirical relationship, $F^+ = (f \cdot X_{\mathrm{te}})/U_\infty$, is utilized because it is more directly applicable in terms of dimensionality to the aerodynamic testing conducted with the HiMVG system. After conducting numerous experiments, Wygnanski[10] documented that optimum flow attachment, at least for subsonic flow on a deflected flap, occurred when $F^+ \sim 1$. This finding was confirmed by data generated during this program. These results will be discussed in a subsequent section of this manuscript.

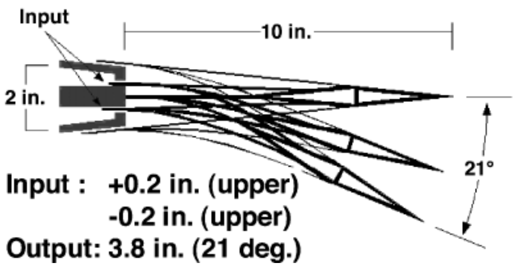
Displacement Amplification Compliant Structures

A compliant mechanism is a relative new class of mechanism that relies on elastic deformation of its constituent elements to transmit motion and/or force. These are in fact mechanisms without joints, neither conventional hinges nor flexural hinges. The mechanisms have compliance distributed throughout the structure and are much more fatigue resistant and easy to manufacture. Distributed compliant systems derive their flexibility due to the topology and shape of the material continuum rather than concentrated flexion at few regions as in plastic hinges. These novel mechanisms can be readily integrated into air vehicle subsystems. Figure 2 shows a comparison of a compliant variable camber flap trailing-edge flap designed at FlexSys, Inc., with the multicomponent mechanical design developed during the Mission Adaptive Wing program.[13] In this example, it is easy to see the potential weight and durability advantages inherent in a properly designed compliant structure.

One of the major barriers in smart structures technology is the displacement, or stroke, available from smart material actuators. In the present project, a displacement amplification compliant structure is

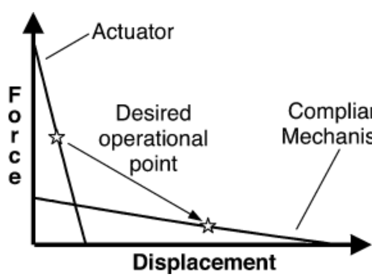


a)

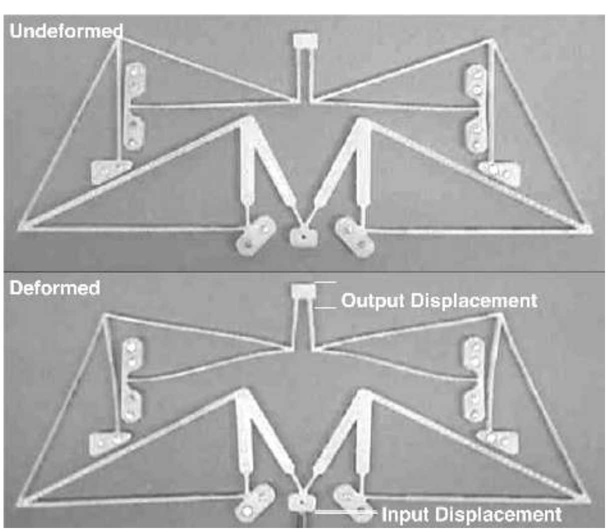


b)

Fig. 2 Trailing-edge flap designs: a) mechanical and b) compliant structure.



a) Actuator tailoring using compliant mechanisms



b) Deformed and undeformed positions of a compliant displacement-amplification mechanism

Fig. 3 Example of a compliant displacement-amplification mechanism.

used as the heart of the HiMVG active flow control system. Augmenting actuators (such as piezoelectric or voice–coil actuators) with compliant mechanisms leads to systems with actuation functionality built into the structure. Such structures distribute the actuation energy derived from an actuator to the application surface. Figure 3 shows the type of motion amplification, compliant structure used to drive the high-frequency, deployable MVG. A voice–coil motor was used to generate an input force in the correct frequency range. The compliant structure is simply used to amplify the displacements provided by the motor into the larger displacements required by the VGs at the surface. The structure is designed to operate over a large working bandwidth below its natural resonant frequency. A second-generation HiMVG design using a piezoelectric actuator has also been designed and will be described in the future research directions section.

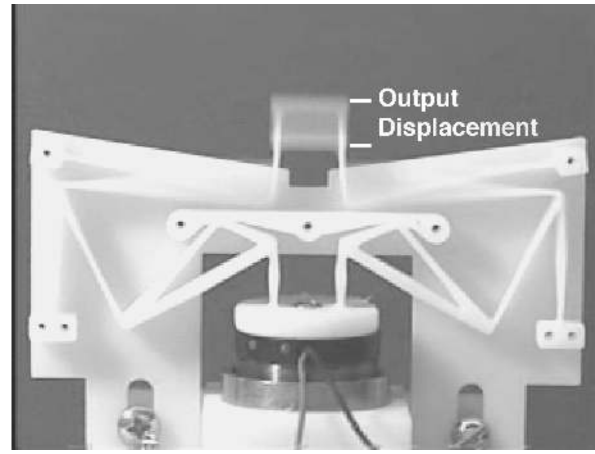


Fig. 4 Actuator-amplifier running at 240 Hz; amplified motion is 5 mm.

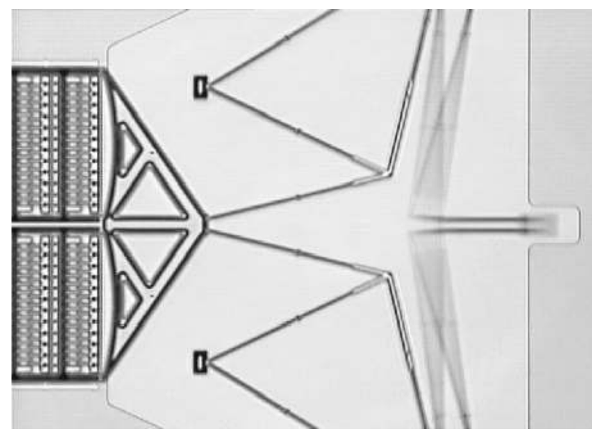


Fig. 5 Electrostatic actuator driving a compliant amplifier at 26.9 kHz.

With use of compliant structures design tools developed in-house, a displacement amplification compliant structure was designed and optimized for the flow control project. The structure was configured to take the 0.25-mm output displacement of a BEI Kimco voice–coil actuator with the required frequency range and amplify the motion to an output of 5 mm, which is the MVG height required to produce the needed vortex stream for effective dynamic flow control, using the aerodynamic model that will be described in a following section. Details of the displacement amplification, compliant structure design, and fabrication process are presented in Ref. 14. Other applications of compliant structure design for displacement amplification are given in Ref. 15. The operational compliant structure and actuator are shown during bench testing in Fig. 4. As noted the system is capable of producing the required displacement amplification at 240-Hz deployment frequency. An indication of the size/frequency versatility of displacement amplification devices is shows in Fig. 5. Figure 5 shows a microelectromechanical system-sized device capable of operating in the kilohertz-frequency range. The compliant structure part of the mechanism was designed at FlexSys, Inc., to produce an output displacement of 20 μm.

High-Frequency, Deployable MVG System

VG Sizing

A corotating VG array was selected for both static and dynamic testing. The individual blade geometry, orientation, and spanwise spacing were configured using the relationships developed and validated by Lin.[7] The flat plate aerodynamic test article, which will

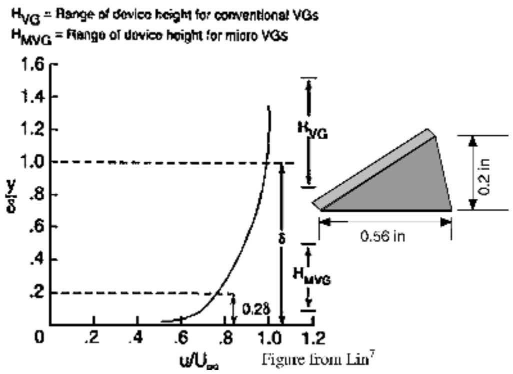


Fig. 6 VG blade design.

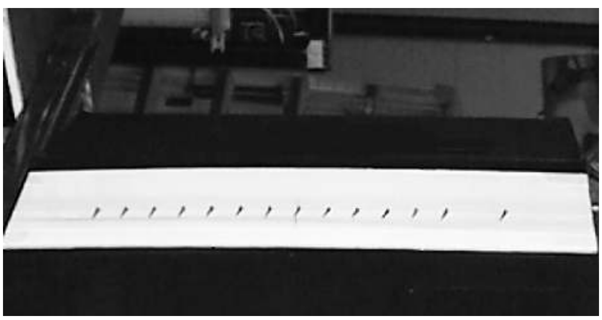


Fig. 7 Installed static VG test array; view from above and ahead of test article.

Fig. 8 High-frequency, deployable MVG test hardware.

be described, was configured to produce a turbulent boundary layer $\frac{1}{2}$-in. (2.54 mm) in height at the VG position located forward of an adverse pressure gradient region produced by a deflected flap. When these design parameters were used, VG blades were configured to the size indicated in Fig. 6. Lin's[7] range of effective MVG blade height is shown on the left side of Fig. 6. Note that the height of the individual blades is 0.2 in. (5 mm) or is approximately 0.4δ. The blades were spaced in a corotating pattern 1 in. apart, and at 23-deg angle of attack to the flow direction. Figure 7 shows the MVG array used for initial static flow control testing.

Active MVG Test Array

The original project plan called for replacing the seven static VGs located at the center of the array with individually actuated, deployable blades for dynamic testing. When suitable piezoelectric actuators with the required displacement/frequency spectrum could not be located during early stages of the program, voice–coil actuators were selected to drive the system. This substitution made it necessary to drive the entire seven-blade array with two actuators, instead of the originally planned individual blade actuation. This design change was made necessary because of off-the-shelf voice–coil size availability. Figure 8 shows the deployable VG array as configured for installation in the aerodynamic test model. The addition of the support beam and seven VG blades reduced the deployment frequency capability of the system to a maximum of 90 Hz, considerably less than the 240 Hz demonstrated by the individual amplifiers, but adequate to meet the reduced frequency bandwidth required for the planned separation control experiment.

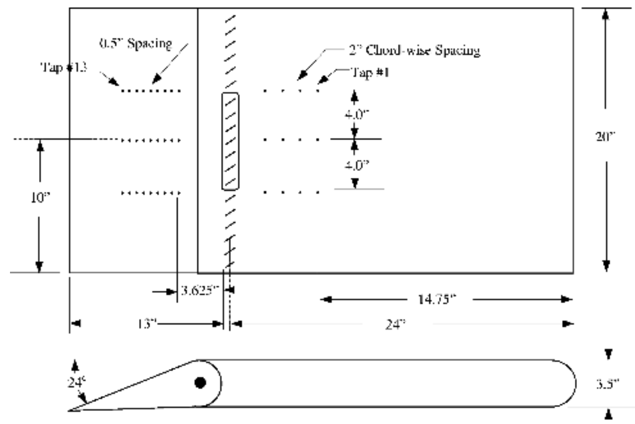


Fig. 9 Wind-tunnel model and pressure instrumentation.

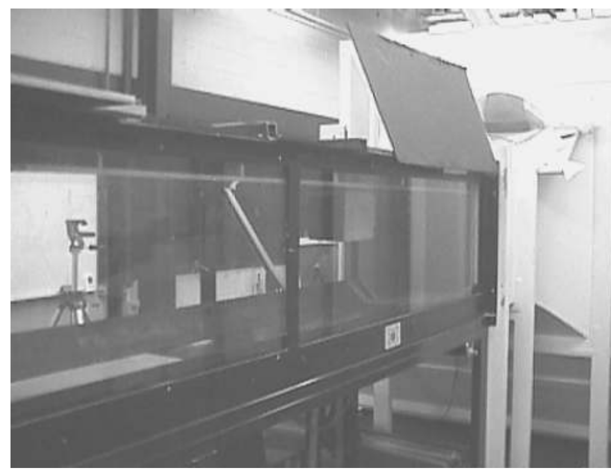


Fig. 10 University of Michigan 2 × 2 ft subsonic wind tunnel.

Flow Control Experiments

Wind-Tunnel Model

The configuration of the aerodynamic test article used during the program is shown in Fig. 9. The model consists of a flat plate forward portion, with a rounded leading edge, mounting a trailing-edge, variable angle flap. The flat plate portion of the test model contained a formed pocket located just forward of the trailing-edge flap position. This pocket was sized to accept the HiMVG test hardware for the dynamic testing portion of the program. During the static VG test phase, the pocket was covered with a plate that mounted the static VG array.

Surface static pressure taps, a total of 39, were installed in 3 chordwise rows as indicated. The box in the center of the array identifies the position of the deployable VGs. Power required to drive the actuators varied across the frequency spectrum, with the lowest power consumption, approximately 5 W/channel, occurring close to the resonance frequency of 90 Hz. The power draw increased to approximately 30 W/actuator in the 40–50 Hz operating range. No attempt was made to design the system for minimum-power operation because this would have required custom designed actuators whose cost were way beyond the funding level of this project. However, note that the power required to operate a similar system in a transonic flow environment does not increase if proper attention is paid to amplifier–actuator design optimization.

Wind-Tunnel Facility

The University of Michigan 2×2 ft subsonic wind tunnel, located in the Department of Aerospace Engineering Research Building, was used for all of the aerodynamic testing conducted during the program. The tunnel, shown in Fig. 10, is an Eiffel-type open-return facility capable of variable test section velocities up to 80 ft/s. Removable panels in the wind-tunnel ceiling provide easy access for model changes. Operation of the wind tunnel was controlled from a single console, which also incorporated all pressure instrumentation control functions.

Instrumentation

The primary instrumentation suite was a surface-mounted static pressure array positioned as shown in Fig. 9. The majority of the taps were spaced in $\frac{1}{2}$-in. chordwise increments on the trailing-edge flap upper surface beginning as far forward on the flap as model construction details would permit. Installing pressure taps in the transition area near the flap leading edge would have provide a more detailed surface pressure map for determining turbulent boundary-layer separation point as a function of flap deflection angle. However, including taps in this area would have complicated the flap deflection mechanism, adding a significant increment to model fabrication cost. The pressure tap pattern used proved sufficient to delineate the upper surface separation characteristics for the test geometries investigated.

A multitube manometer board, which used water as the working fluid, was used to measure pressures. Individual static pressure taps were read sequentially and recorded, using a Scanivalve™ system. Pressure readings were averaged over 500 ms before being recorded. Each pressure was corrected in the data reduction program, using measured test section static temperature.

Flow Control Results

Static

The focus of initial testing was to establish an appropriate adverse pressure gradient, separating flowfield, on the flap upper surface. This was accomplished by deflecting the model trailing-edge flap until the pressure instrumentation indicated boundary-layer separation had occurred at the forward flap pressure station(s). The flat plate was mounted vertically in the wind tunnel, at zero angle of attack to the freestream, for all testing. No VGs were used during this test phase. Also, during this initial test phase, a boundary-layer rake was used to confirm the presence of a turbulent boundary layer, approximately $\frac{1}{2}$ in. thick, at the position on the flat plate (Fig. 9), where the VGs would be located for testing.

A flap deflection angle of 24 deg produced the pressure pattern shown in Fig. 11. Note that the surface static pressure readings show no low-pressure region (no VGs case) on the flap upper surface, indicating the boundary layer has separated in the flat plate/flap transition area. Included in Fig. 11 is pressure data taken with the static VG pattern (Fig. 7) in place. These data show a decrease in pressure at the flap aft tap positions, but none at the forward positions. This indicates that the boundary layer is separating in the flat plate/flap transition area, but that the vortical flowfield induced by the VG array is producing an organized separated flow region above the flap that has a pronounced effect on the flap upper surface pressures. This same effect was recorded during subsequent testing using the dynamic VG array position for static flow control measurement, that is, the dynamic VGs were fixed in the extended, 5-mm position. The pressure data shown are for the centerline row of pressure taps only.

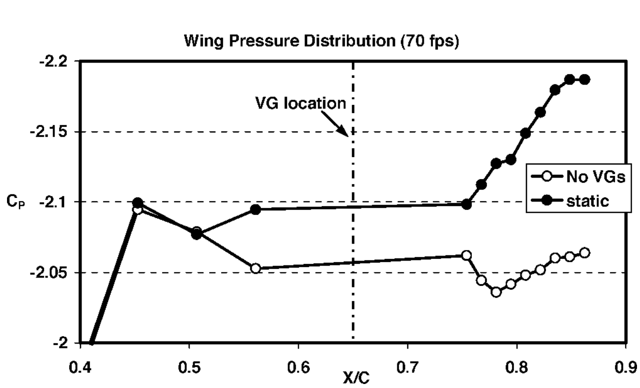


Fig. 11 Aerodynamic model pressure, with and without static VGs present.

Dynamic

For this test phase, the static VGs at the center of the test array were replaced with the HiMVG test hardware shown in Fig. 8. The high-frequency, deployable MVGs were actuated, during the dynamic test phase, through a frequency range of 30–70 Hz using the electronic setup shown in Fig. 12. The dynamic flow control test series ran smoothly, although several adjustments had to be made to the VG mounting beam mass to assure full stroke deployment, 5 mm, was available at all test frequencies.

Figures 13a and 13b summarize the critical results of the dynamic flow control testing. These data are presented in Figs. 13, which plot model upper surface suction in inches of water for the upper surface centerline static pressure taps, for the spectrum of frequencies tested. Figure 13a is for a test velocity of 55 ft/s and Fig. 13b for a test velocity of 70 ft/s. When the data are examined, one can readily see that operating the deployable VGs in a high-frequency mode (deployment height 5 mm) produced flow attachment on the forward portion of the flap upper surface where none was present with the VGs statically deployed. Additionally, the oscillatory frequency spectrum for best flow attachment performance, judged by the suction magnitude at tap locations near $x/c = 0.75$ (the two forwardmost flap pressure locations), closely follows the subsonic flow control results

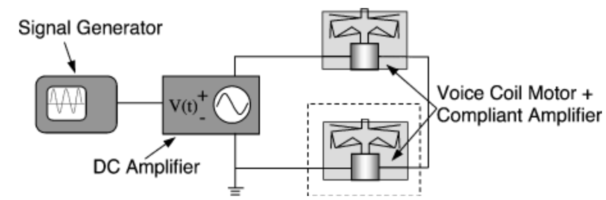
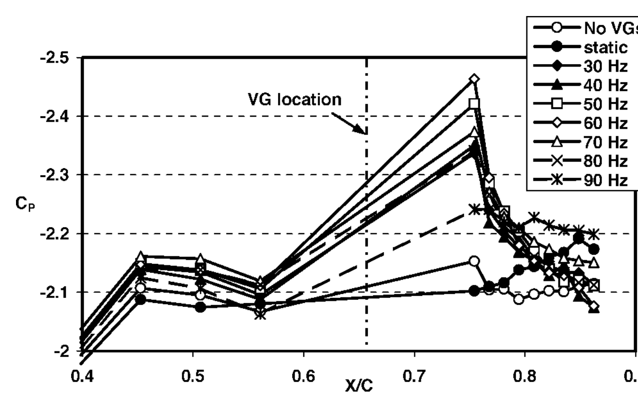
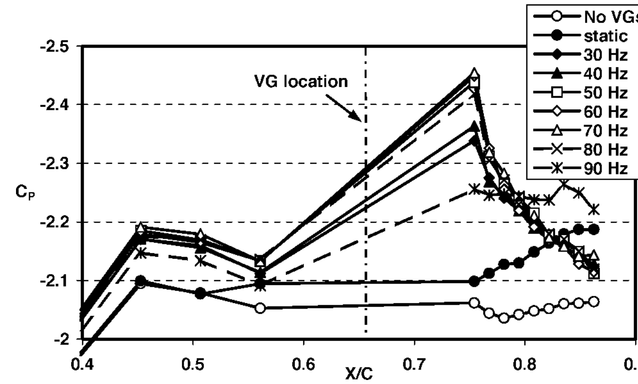


Fig. 12 Voice–coil motor wiring diagram.



a) Wing pressure distribution, 55 ft/s



b) Wing pressure distribution, 70 ft/s

Fig. 13 HiMVG dynamic test results.

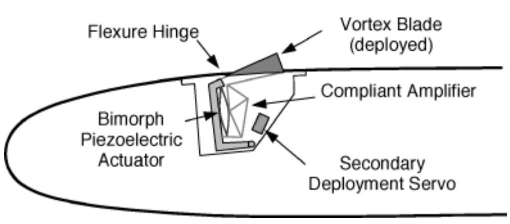
of Wygnanski.[10] For example, using the reduced frequency definition of Ref. 10 ($F^+ = f \cdot X_{te}/U$), the F^+ values where the HiMVG system performed best approach the value of $F^+ = 1$. The trend in deployment frequency for best flow control is consistent with the Ref. 10 database, 70 Hz ($F^+ = 1.08$) producing the best results at the higher test velocity and 60 Hz ($F^+ = 1.18$) performing better at the 55-ft/s test condition. Note that the dynamically deployed vanes always outperformed the statically deployed vanes, although great care was taken to limit the maximum penetration to the same level (5 mm $\approx 0.4\delta$). This reinforces the concept that the addition of periodic excitation into a separating turbulent boundary layer increases the momentum transfer across the shear layer, enhancing its resistance to separation under adverse pressure gradient. Even if the flow is not fully attached, the lift can be significantly enhanced by the introduction of periodic excitation into the separated shear layer.[16]

Additional pressure taps in the vicinity of the flat plate/flap transition area would have been helpful in quantifying more accurately the optimum deployment frequency for turbulent boundary-layer separation control. Testing deployment frequencies in 5-Hz increments and acquiring pressure data at additional tunnel speeds would also have been helpful in this area. However, measured results with the available instrumentation proved sufficient to quantify the efficacy of the mechanical flow control device tested. The data taken were repeatable and, in the bottom line, produced turbulent boundary-layer separation results comparable to the best oscillatory pneumatic systems.

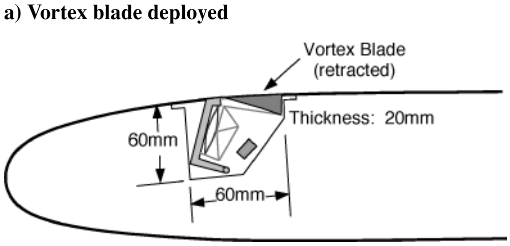
Future Research Directions

The next step in the development of a versatile, mechanical HiMVG flow controller must address system integration issues. A second-generation design developed in the latter stages of the current program is shown in Fig. 14. This design attacks shortcomings present in the demonstrated system and opens up additional flow control applications where size and power are first priority design parameters.

First the VG blade(s) is flush with the aerodynamic surface when retracted, eliminating the surface pockets present with the current design. An indexing actuator is used to deploy the blade to an optimum extension position around which the blade is oscillated. During the course of the current experimental program, it was determined that oscillating the blade through the 2 mm of boundary layer adjacent to the surface had no effect on downstream vortex strength. For maximum effectiveness, the blade should be extended to the position of maximum vorticity production and oscillated around that position at the critical frequency. However, if the device is used for dynamic stall control, an area of high current interest in this program's sponsoring agency, different flow mechanisms are involved, and the indexing position around which the VG oscillates may need to move as the airfoil is in the pitch-up process.



a) Vortex blade deployed



b) Vortex blade retracted

Fig. 14 Concept of second-generation HiMVG device.

A second and critical element of the second-generation design is the use of compact, energy-efficient, electrically driven actuators to drive the oscillation. Devices, such as bimorph piezoelectric actuators from Piezo Systems, Inc., have been identified that will provide the necessary deflection vs frequency performance needed for second-generation HiMVG device applications. Piezoelectric actuation is necessary to configure the compact system conceptualized in Fig. 14. Piezoelectric devices were initially considered for actuator use in the current program, but were replaced by voice–coils when the initial testing of several piezoelectric samples failed to produce the deflection/frequency characteristics required.

A research opportunity exists to explore the application of HiMVG devices for aircraft dynamic stall control. In the past, much has been written about flow control for enhanced maneuverability and extended operating times in the region beyond aircraft static maximum lift. The second-generation HiMVG device, properly developed, would bring a new active flow control concept to this arena, which will work effectively in a transonic flow environment and only requires a small amount of electrical power for operation.

Conclusions

This initial development of a mechanical, high-frequency active flow control device accomplished the following items related to amplifier–actuator design and fabrication and active flow control demonstration:

For the displacement amplification compliant structure, the following was accomplished.

1) There was successful design and fabrication of a compliant structure with a displacement amplification of 20:1.

2) There was integrated design and demonstration of an amplifier, that is, actuator system that achieved an output stroke of 5 mm while operating in the frequency range between 0 and 240 Hz.

3) A dual amplifier-actuator system was developed and demonstrated that drives seven deployable VG blades in unison and operates in the frequency range between 0 and 90 Hz.

4) A compact second-generation HiMVG device was conceptually designed.

For flow control, the following conclusions were reached.

1) The MVG geometries developed and demonstrated by Lin[7] in the static flow control environment work well in a dynamic flow control system.

2) The oscillatory flowfield produced by a deployable VG array is an effective means of energizing a separating turbulent boundary layer.

3) The HiMVG system when operating at a reduced frequency of $F^+ \sim 1$ produces separation control results, in a subsonic flow environment, comparable to the best oscillatory pneumatic systems.

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