The AVT-239-RTG Multidisciplinary Performance Assessment of Innovative Control Effectors for Next Generation Military Air Vehicles: Summary and Outlook

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ABSTRACT

Next generation military aircraft will confront increasingly contested and increasingly sophisticated threat environments. To enhance the survivability of future aircraft in these scenarios will require new approaches to flying aircraft. The NATO AVT-239 RTG investigated the application of novel flight control technologies to aircraft manoeuvring. Candidate active flow control (AFC) technologies were identified, developed, and assessed against key vehicle performance and vehicle integration criteria. The study revealed that AFC systems occupy less volume and have lower weight than conventional systems but that the readiness levels are still relatively low. Overall, the technology is both feasible and reasonable for application to next generation air vehicle platforms, but further investment is required. In this paper, we identify areas for technical and capital investment including how the vehicle design process might be re-structured to better exploit AFC, how to optimize AFC effector design and what CFD approaches are required to assess effector performance. In addition, we address the challenges of AFC system integration and reliability alongside conventional control systems and the control non-linearities the coupling of those systems might present. The discussion alludes to activities in planning for the AVT-350 follow-on activity.

1.0 INTRODUCTION

Next generation penetrating UAVs will confront an increasingly contested and more sophisticated threat environment. The challenges associated with operating in this environment present an opportunity to explore advanced aerodynamic technologies that enable low detectability, increased availability and high agility during enhanced, evasive tactics. The NATO AVT-239 group used this future scenario to motivate a study of advanced aerodynamic technologies that eliminate the complex, moving flight control surfaces that constrain current UAV performance.

The outcome of the AVT-239 study was a general framework in which active flow control (AFC) technologies could be assessed against typical conventional aircraft systems used for flight control. In the spirit of making a multidisciplinary evaluation, the framework assessed AFC technologies from an aircraft system perspective, examining the dependencies between the AFC system and other aircraft systems and how the AFC modifies the broader features of a vehicle design. The framework used existing design tools and approaches to evaluate and assess the system level performance of AFC for flight control including a variety of '-ilities' requirements. The multidisciplinary assessment framework used a quality function deployment (QFD) approach for exploring the strengths and weakness of the AFC technology (Miller, Williams, Warsop, & Smith, 2019). This approach revealed the areas that, within the scope of the study, required further design and technical development (Miller, et al., 2019).

This summary and critical review of the AVT-239 AFC assessment framework aligns with the AVT-324 specialist meeting objectives because it uses future design requirements to craft an objective multidisciplinary assessment approach that is built on current design methods and uses the assessment to make recommendations for realistic next steps. The paper will start with a summary of the multidisciplinary process that AVT-239 evolved for integrating and assessing active flow control (AFC) at the conceptual vehicle design level. It will then present and discuss the perceived weaknesses/deficiencies in the AVT-239 assessment and make recommendations regarding further research to improve the design process. We will suggest directions for future study that advance the case for AFC as part of a next generation vehicle design study.

For the study described here, the AFC effectors encompass a broad range of technologies that alter the streamlines of the flow over an aerodynamic body, e.g. positive, negative, or zero net mass addition at the surface, but we constrain the prospective technologies to ones that do not involve a mechanical change to the outer mould line of the vehicle.

2.0 AVT-239: INNOVATIVE CONTROL EFFECTORS FOR MANEUVERING OF AIR VEHICLES

The NATO STO AVT-239 Research Task Group came together to investigate the application of novel flight control technologies to aircraft maneuvering. The broader task was to identify candidate technologies, develop a system representation for them, and then assess them against key vehicle performance and vehicle integration criteria (e.g. complexity, maintainability, reliability).

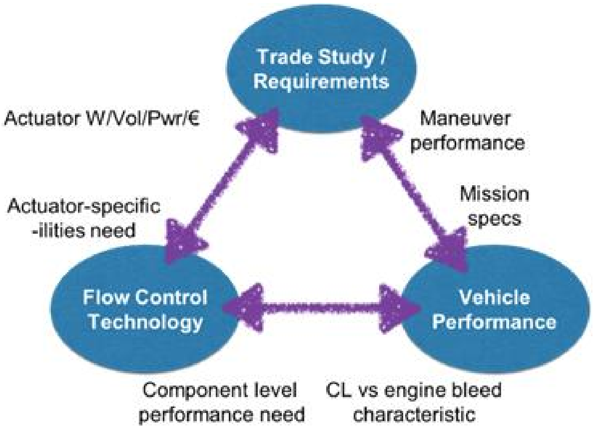


Figure 1: AVT-239 sub-groups and example interactions.

2.1 Task Group Structure

To accomplish the goals of the task group, the participants were divided in to sub-groups, each associated with one of the key components of the assessment: the flow control effector technologies, the vehicle performance evaluation, and the trade study and system requirements evaluation (Figure 1). Although working largely independently, there were important interfaces and interactions between the sub-groups with each relying on inputs from the other sub-groups to accomplish their tasks.

The Flow Control Technology sub-group was composed of participants bringing expertise with specific flow control technologies. This group determined which technologies were likely candidates to deliver vehicle maneuvering control. The group selected specific AFC technologies for study and were responsible for defining a consistent means for comparing the relative merits of different flow control technologies. In this study, all the control technologies used some form of steady blowing with the figure of merit being the change in aerodynamic performance as a function of momentum coefficient (C_μ) or percent engine bleed flow ($\% \overline{W}_{bleed}$). The group members undertook the task of doing the component level evaluations of the candidate technologies. These evaluations were done with both experimental testing in wind tunnel facilities and numerical simulations, and when possible, experiments and simulations were performed for the same configurations at the same test conditions (Re, Ma).

The Vehicle Performance sub-group assessed the capabilities of component level AFC technologies to deliver the required vehicle mission performance. In coordination with the Trade Study/Requirements sub-group, this team defined figures of merit for evaluating a flow control technology at the vehicle level. As the AFC technologies of interest all required engine bleed air, the figures of merit were based on the average and peak engine bleed demand during the prescribed mission. The average mass flow rate demand gave an estimate of the impact of AFC flight control on engine TSFC and hence range. The AFC performance measures were obtained from the Flow Control Technology sub-group and were integrated into the flight control laws of a 6-DOF MATLAB-based flight simulator. The flight simulator was then run for the mission scenarios with repeated runs to build up statistically relevant estimates of the bleed air requirements.

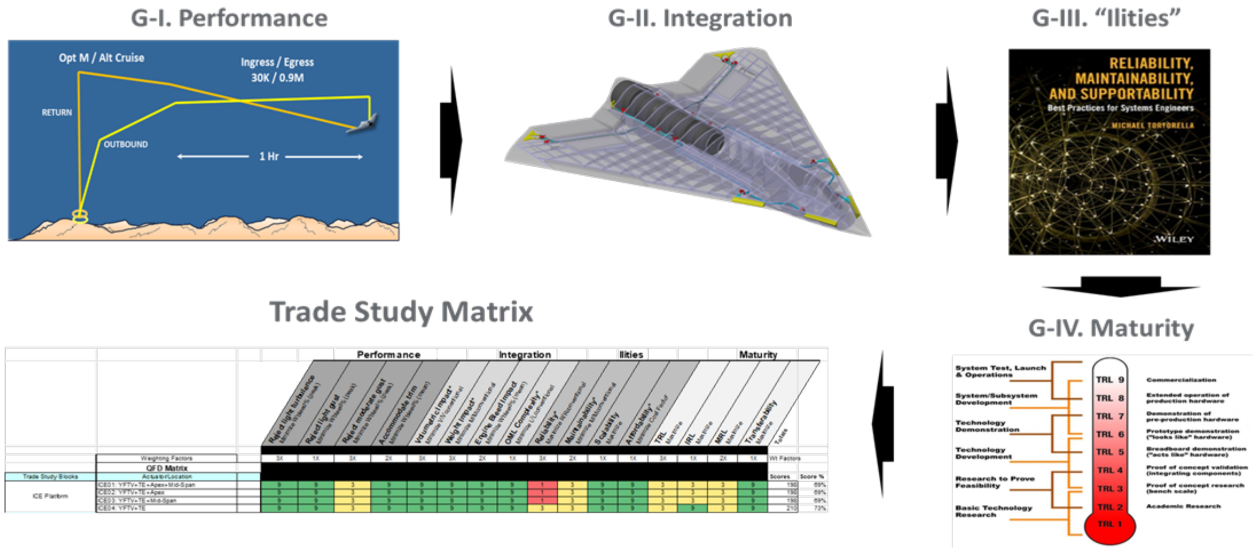


Figure 2: Trade Study Process Incorporates Analysis and Design Task Across 4 Groups of Metrics

The Trade Study & Requirements sub-group defined the overall requirements for the study, identified the mission profiles for the vehicle performance trials, and conducted the trade studies in which the control technologies were evaluated against the system performance requirements. This evaluation used a Design of Experiments (DOE) Quality Function Deployment (QFD) matrix to give qualitative, relative comparisons with objective metric scoring. The approach is based on the statistical analysis methods of Box et al. (Box, Hunter, & Hunter, 2005). The QFD approach assessed each technology in four areas: performance, integration, '-ilities', and maturity. These four assessment areas (highlighted in Fig. 2) have defined metrics and grading criteria (Miller, Williams, Warsop, & Smith, 2019).

2.2 Vehicle Platforms

In the first year of the activity, the three sub-groups, working together, identified two baseline aircraft configurations for the flow control effector evaluations. The criteria for candidate vehicle platforms were that (1) the vehicle should be characteristic of a next generation combat vehicle, preferably tailless; (2) a vehicle performance and control database for the platform was readily available in the open literature; and (3) abiding criteria (1), the two platforms should be sufficiently distinct to provide an assessment of the effector performance against different aerodynamic characteristics, e.g. wing sweep. The two vehicles selected were based on the SACCON (Cummings & Schutte, 2010) and the Lockheed Martin ICE-101 (Dorsett, Fears, & Houlden, 1997), both characteristic of a next generation military aircraft; that is, tailless with highly-swept wings (Figure 3). Note that in the early part of this study, the planform profile but not the lofting of the ICE-101 was available to the group. To prevent a delay in initiating the AFC evaluations, a lofting profile based on the SACCON was used to complete the design of the wind tunnel model for testing. This shape was then retained for the remainder of the study.

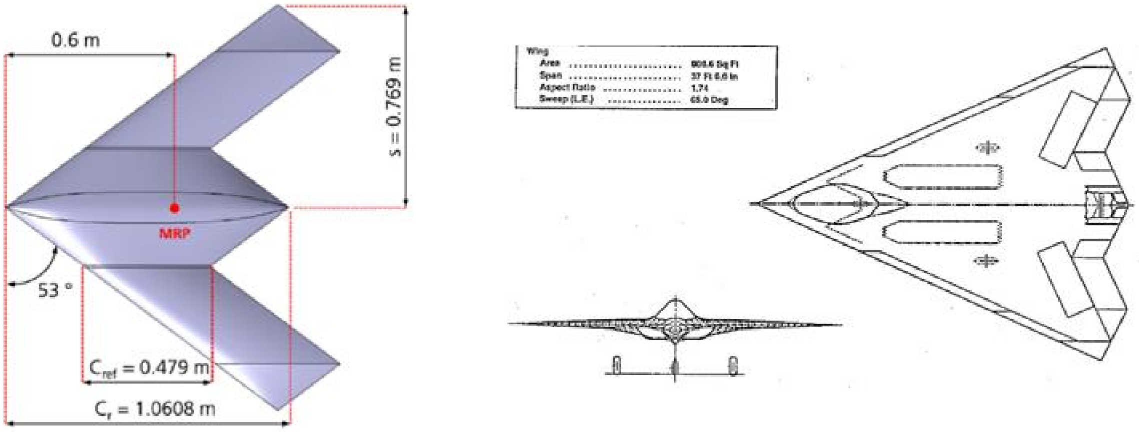


Figure 3: SACCON platform (left) and ICE-101 platform (right).

2.3 Mission Profile

Also identified in the first year was a set of three mission scenarios under which the performance of the technologies could be evaluated against conventional flight control effectors. The mission profiles were (1) ingress/cruise, (2) egress with high maneuverability, and (3) high-lift take-off and landing. Although AFC performance data relevant to all three missions were collected in the course of this task group, a full system assessment was only performed for the ingress mission profile.

The flight conditions for the ingress profile were Mach 0.9 and 30,000 ft with light-to-moderate turbulence over 99% of the flight time and moderate gusts for the remaining 1% of the flight time (ref. MIL-HDBK-1797). As described above, performance was assessed against the required engine bleed mass flow rate as a percentage of the total engine mass flow.

3.0 RESULTS OF ASSESSMENTS

As shown in Figure 1, the success of this effort hinged on close and timely connections between the three sub-groups, but each group individually produced significant accomplishments that ultimately contributed to the overall AFC assessment framework.

The AFC technologies considered here included circulation control slots along the trailing edge span of the wings (TECC), steady blowing and sweeping jet blowing at various locations along the wing leading edge (APEX) and mid-span locations (MID-SPAN), and fluidic approaches to vectoring thrust from the engine exhaust stream (YFTV). Performance data for these control inputs were collected in wind tunnel test campaigns and obtained from numerical simulations (Williams, Seidel, Osteroos, & McLaughlin, 2019) (Warsop, Forster, & Crowther, 2019) (Phillips, et al., 2019). Example results for TECC on the ICE for pitch control are shown in Figure 4. Here we show the shift in the pitching moment with C_m and demonstrate how the aircraft can be trimmed in pitch at different angles of attack.

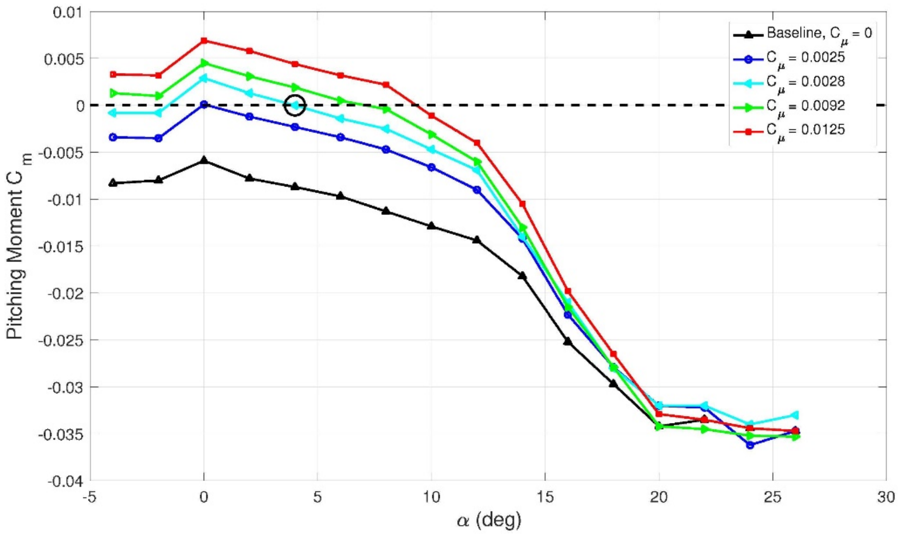


Figure 4: Pitching moment coefficients with both left and right upward blowing trailing-edge AFC control effectors.

Flight control simulations assessed the control requirements and performance for an aircraft that uses only active flow control effectors for trim flight control during the ingress mission. Flight control force and moment data, provided by the flow control technology group, were used to create a control matrix and then to estimate the expected AFC performance demands during a mission. Active flow control trim conditions were compared to conventional control effector trim. The mass flow rate requirements for the bleed air system to compensate for light and moderate turbulence and discrete gusts on flight at M = 0.9 cruise conditions were documented (Niestroy, Williams, & Seidel, 2019) (Hutchin, 2019). The peak engine bleed mass flow requirement to overcome the moderate gust case was 1.8% and 3% for the SACCON and ICE configurations respectively.

A design of experiments trade study approach was employed to assess the feasibility of integrating a suite of active flow control technologies for the vehicles in comparison to a conventional mechanical flap-based control suite. As a basis to evaluate an integrated AFC system, a basic layout and internal arrangement of the ICE platform was created. It was assumed that the SACCON vehicle would have a similar layout of comparable size and weight. Figure 5 shows the basic arrangement of the AFC effector flight control suite for the baseline ICE configuration. The AFC effector suite includes a bilaterally symmetric installation of control effectors distributed at four principal locations on the aircraft. The control effectors are located along the (1) nozzle wall using yaw-plane fluidic thrust vectoring (YFTV), (2) trailing-edge (TECC) outboard, (3) leading-edge (LE) apex, and (4) LE mid-span. The AFC effector suite is distributed to provide multiple options for control power in aircraft pitch, roll, and yaw axes. Each AFC effector is supplied with bleed air extracted from the inter-stage port of a representative modern military turbofan engine. The bleed air is transported to each AFC location via a valve and duct assembly.

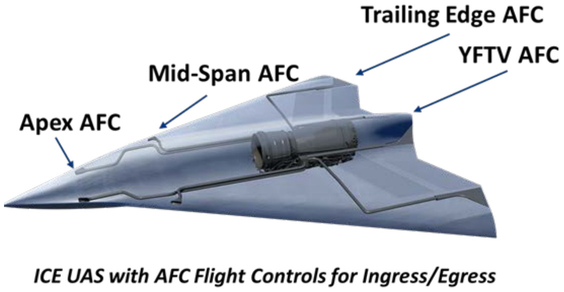
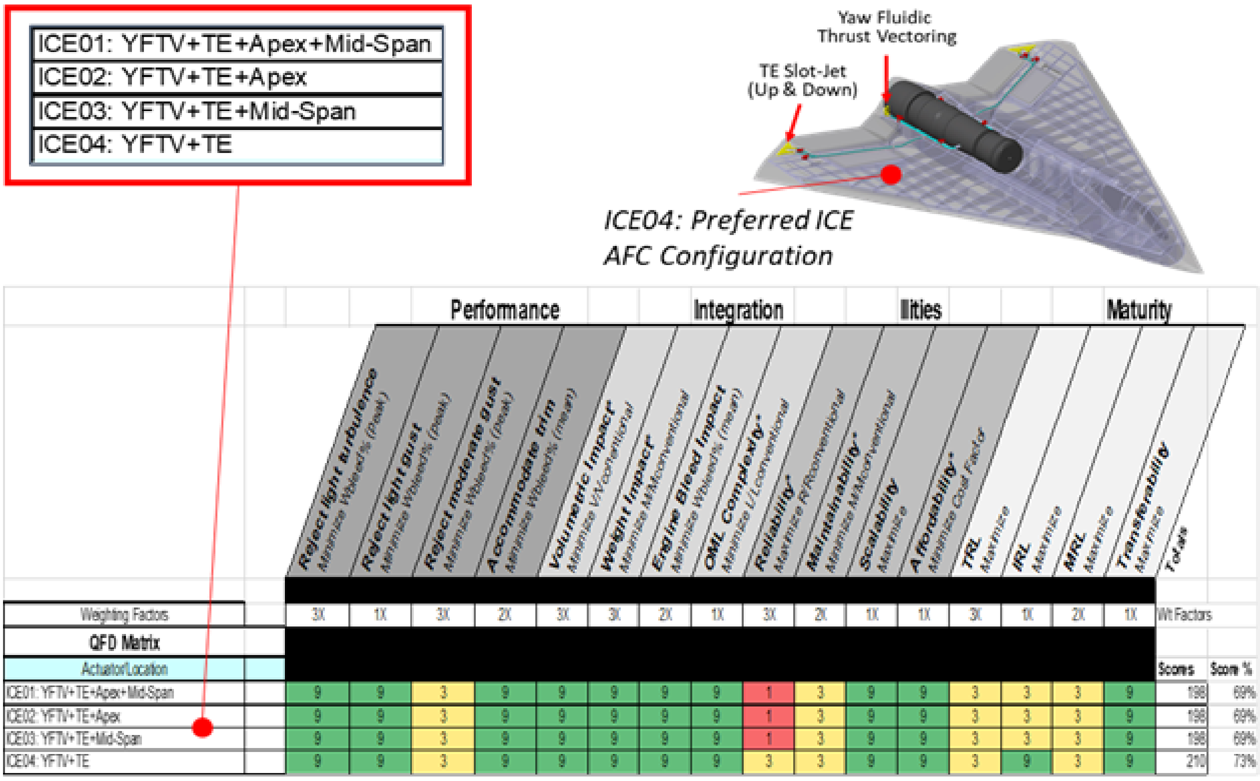


Figure 5: ICE with AFC Flight Control Suite.



	Performance				Integration				Ilities				Maturity					
	Reject light turbulence Minimize Wbleed% (Peak)	Reject light gust Minimize Wbleed% (Peak)	Reject moderate gust Minimize Wbleed% (Peak)	Accommodate trim Minimize Wbleed% (mean)	Volumetric Impact Minimize V/Vconventional	Weight Impact Minimize M/Mconventional	Engine Bleed Impact Minimize Wbleed% (mean)	OML Complexity* Minimize L/Lconventional	Reliability* Maximize R/Rconventional	Maintainability* Minimize M/Mconventional	Scalability Maximize	Affordability* Minimize Cost Factor	TRL Maximize	IRL Maximize	MRL Maximize	Transferability Maximize	Totals	
Weighting Factors	3X	1X	3X	2X	3X	3X	2X	1X	3X	2X	1X	1X	3X	1X	2X	1X	Wt Factors	
QFD Matrix																		
Actuator/Location																	Scores	Score %
ICE01: YFTV+TE+Apex+Mid-Span	9	9	3	9	9	9	9	9	1	3	9	9	3	3	3	9	198	69%
ICE02: YFTV+TE+Apex	9	9	3	9	9	9	9	9	1	3	9	9	3	3	3	9	198	69%
ICE03: YFTV+TE+Mid-Span	9	9	3	9	9	9	9	9	1	3	9	9	3	3	3	9	198	69%
ICE04: YFTV+TE	9	9	3	9	9	9	9	9	3	3	9	9	3	9	3	9	210	73%

Figure 6: QFD Results: ICE01-04 Feasible; ICE04 Preferred Based on KPP Sensitivities.

The trade study employed four categorical metric groups including: (1) flight control performance, (2) aircraft integration, (3) technology "ilities" including reliability, maintainability, scalability, and affordability, and (4) technology maturity. In practice, the trade matrix features four configuration combinations (labeled ICE01-04) of the AFC effector suite (Figure 6). Four groups of trade study metrics each with four key performance parameters (KPPs) are employed to represent the AFC performance and platform integration ‘opportunity cost’. Group I (or G-I) measures AFC flight control performance on the ICE platform; G-II measures the integration impacts; G-III measures the so-called ‘ilities’ impacts; and G-IV measures the technology maturity.

The trade study suggests that AFC technology is both feasible and reasonable for application to the two platforms investigated and can provide the required control power during an ingress/egress mission. A summary of key conclusions include:

- Flight control simulations show that sufficient control power can be generated across all key performance parameters (KPPs) and at a peak bleed flow rate acceptable for a modern turbofan engine. The performance metric results suggest AFC is feasible from a performance standpoint.
- The nominal AFC engine bleed impact KPP is approximately 0.5%. This level of bleed flow is acceptable to most modern turbofan engines and suggests a 1% impact to aircraft range.
- The AFC system volume and weight impact for the ingress/egress mission phase is of the order of 5-10% and 25%, respectively, of the conventional control system.
- The size, weight, and outer mould line impact results suggest very reasonable levels for AFC and the possibility to integrate alongside a conventional system (as a redundant control to permit safe developmental and operational testing).
- The preferred AFC technology for both the ICE and SACCON configurations features trailing edge tangential blowing/circulation control supplemented by yaw thrust vectoring for the ICE configuration.
- DoD readiness level KPPs for technology and manufacturing are 3-4 for the configurations considered. Readiness level KPPs for integration are the least mature with the integration interaction between different control effectors, AFC and conventional, least understood.
- The transferability KPP suggests that all configurations are excellent. A level 6 suggests the technology can be hypothetically developed on one UAV platform and then “cross-decked” or transferred readily with no major developmental obstacles from an aerodynamic standpoint.

Of the technologies investigated, trailing edge tangential blowing/circulation control (TECC) and yaw fluidic thrust vectoring (YFTV) proved to be the most effective and efficient for the transonic ingress/egress mission role. This was probably to be expected since it is a technology that modifies the ‘inviscid’ circulation around the wing, in contrast to ‘viscous’ based control technologies, such as, separation control. Circulation control functions most efficiently in terms of minimizing the engine bleed mass flow for a given control effect when the slot blowing velocity is maximized. This leads to operating the control effector at supercritical conditions to achieve supersonic nozzle exit velocities. The circulation control technology has been shown to be an effective and efficient technology for the subsonic flight regime, but it is uncertain if the technology will be effective at supersonic flight speeds, because lift is generated through shock-generated pressure differences.

Fluidic thrust vectoring, particularly in the yaw plane, has been shown to be a useful and efficient technology for finless configurations such as ICE (Miller & McCallum, Prospects for Fluidic Thrust Vectoring Technollogy on a Next-Generation Air Vehicle, 2013). While not explored for the SACCON configuration in this study due to constraints on available data and effort, it is likely that this technology will be equally applicable to the latter configuration class. However, it appears that a well-designed circulation control system is capable of achieving adequate yaw control authority when used in differential mode to take advantage of its ability to modulate both thrust and drag on opposite wings.

4.0 INCORPORATING AFC INTO EARLY CONCEPTUAL DESIGN

The AFC technical community has speculated as to the prospects of incorporating AFC technology as a primary design variable introduced early in the conceptual aircraft design process (e.g., along with aircraft configuration variables, stability and control, propulsion, structures, subsystems, etc.). Initial prototypes of AFC-controlled air vehicles will likely be derivatives of existing conventionally controlled designs and, therefore, may represent meaningful, but ‘evolutionary’ or incremental gains in vehicle performance and capability. However, some argue that if AFC were incorporated as a primary conceptual design parameter, a ‘revolutionary’ capability may be obtained.

The exact nature of this potential capability is yet to be seen but might involve a radically different aircraft configuration that does not depend upon a conventional lift/drag characteristic for the wings or control surfaces. For example, one concept that has been discussed is a super-maneuvering combat vehicle that uses differential high-rate separation control to produce much higher rates of turning than mechanically actuated control surfaces. Another such concept might use highly swept lifting surfaces with leading-edge vortex control to produce rapid changes in lift/drag. Yet another uses unconventional vehicle configurations to meet non-aerodynamic vehicle capability gains (e.g., for structural efficiency, weight reduction, advanced mission systems integration, survivability, etc.) with integrated AFC to permit the configuration to be flown and controlled as if it were a conventional design.

Ultimately, the ability to realize these designs will be dependent upon our AFC prediction capability that will need to be integrated into our early conceptual design models.

5.0 AVT-239 CHALLENGES & RECOMMENDATIONS FOR FUTURE STUDY

AVT-239 considered two advanced vehicle concepts initially designed only with conventional flight control in mind and demonstrated that AFC could be used to provide full flight control of these vehicles during a portion of a mission profile. Over the course of the AVT-239 effort, the team uncovered many opportunities for improvement in the evaluation framework. Some of these opportunities suggest revisions to the overall framework, and some are more closely aligned with the detailed tasks that contribute to the framework. In the sections below, we address these items as they relate to vehicle design with AFC, to the evaluation of the control effects and utility of different AFC effectors, to flight control, and to system integration.

5.1 Detailed Design with Active Flow Control

The starting point for the AVT-239 effort was to adapt a pre-existing vehicle design. The ICE airframe outer mould line (OML) was pre-defined, and AFC effectors were added during the conceptual design of the ICE/SACCON aircraft. Some aerodynamic data was available for the LM-ICE-101, but the control power (derivatives) that would be available from the AFC effectors was unknown. The AFC effectors were designed as a “best guess” at providing sufficient pitch/roll/yaw control power for the mission requirements. Wind tunnel measurements and numerical simulations were then used to determine the control effectiveness, and vehicle control evaluations in the flight simulator followed, but at a late stage in the design process. In cases where a preliminary airframe OML is already defined, a better approach to the initial design of the AFC system would be to do flight simulations first before design and wind tunnel testing begins. If the forces and moments required for the aircraft to meet its mission requirements are known in advance, then the wind tunnel testing could be approached differently. For example, control effector sizing and placement on the aircraft would be the primary objectives of the wind tunnel testing, instead of simply documenting the control power at fixed locations. Creating a database of control derivatives as a function of actuator location on the vehicle would be essential for any optimization scheme, such as, multi-disciplinary design analysis and optimization methods MDAO. The force and moment information for the mission would form the constraints in the optimization. Cost functions could be built around bleed air and pneumatic power requirements. MDAO could be also be used to guide modifications of the aircraft shape.

Questions about AFC optimization are important. The term “optimal” can be defined by the design that requires the least amount of bleed air (or perhaps pneumatic power) required to achieve a necessary level of control. Above we addressed briefly the issue of optimal locations for AFC, but what about the shapes of the effectors? For example, on the ICE vehicle, the apex effectors were intended to be the primary yaw control effectors. The slot length was fixed in the initial wind tunnel measurements, but tests on a flight test vehicle indicated that shorter slot lengths might provide more yaw moment with less mass flow. How then does one go about determining the optimal shape for the AFC effectors? Parametric studies using numerical simulations and/or experiments would be necessary in the absence of some understanding about the AFC interaction with the external flow field. The latter requiring lengthy CFD or experimental test campaigns. Ultimately, a parametric study with systematic variations in the effector shape would be required to verify the optimality of the design, but armed with the understanding of the actuator-to-flow field interaction the parametric study would be less trial-and-error.

Yet another alternative optimization would be to fix the effector locations, and explore modifications to the shape of the flight vehicle to enhance performance. Returning again to apex actuation on ICE, these effectors create a yaw moment by creating a flow field asymmetry that lowers the surface pressure on the actuator side of the nose and increasing the pressure on the opposite side of the nose. It might be possible to enhance the control effector performance by increasing the projected area of the nose in the vicinity of the apex control effector.

A central challenge to the optimization of AFC is how to deploy computational and experimental efforts to best effect to provide the required performance data. The vast majority of aircraft design simulations are carried out using fast and reliable methods solving a set of simplified equations (e.g. panel methods). While these methods are highly optimized, they only access a limited parameter space within the flight envelope, and to date, no attempt has been made to incorporate active flow control inputs. One approach to overcome the discrepancy between the required detail in the simulation (and the associated compute time) and the large number of design iterations necessary could be the emerging field of surrogate modeling. In this approach, existing data (e.g. from experiments, simulations, or flight tests on similar systems) are analyzed using machine learning tools to discover patterns in the measured impact of flow control actuation on aircraft performance, loads, etc. These then form the basis for AFC models in the design iterations.

5.2 Understanding and Predicting Effector Performance

The CFD toolsets used at the detailed aerodynamic design and development stages require further substantiation and consolidation of the approaches taken for their application. This will require their validation against reliable experimental reference data for relevant flow conditions. While low-speed experimental data related to AFC technologies are becoming more widely available there remains a paucity of quality experimental data relevant to the conditions often associated with full-scale application. Equally important to the evaluation of AFC is sub-scale testing, and this too includes wind tunnel tests where the effect of Reynolds number and Mach number are explored. This is particularly critical since flow control aims to locally alter the flow field to achieve global changes. The effectiveness of flow control is therefore directly connected to the interaction of the flow control input with the local flow field. Altering the Reynolds number, and to some degree changing the Mach number, could have a profound effect on the effectiveness of flow control on a given platform. Moreover, many AFC technologies rely on geometric features having very small size at full-scale or comprise numerous small-scale features distributed over the airframe. Replicating and testing these AFC devices at representative model scales becomes very challenging. Research and development is required in the near future to mature wind tunnel testing approaches (including model design and manufacture) to enable AFC testing to be undertaken on relevant configurations and flow conditions. Clearly, test data for AFC performance at transonic freestream conditions on both simplified models and complete configurations will be essential to provide the levels of confidence in computational toolsets and design methods required to advance the maturity of AFC technology in the near future.

5.3 Flight Control with AFC Effectors

The effectiveness of a conventional control surface and its variation with flight parameters (flight speed, angle of attack, control deflection angle, actuation rates etc.) is reasonably well understood and largely monotonic and linear. On the other hand, the effectiveness of AFC effectors can be much more complex and, in some instances, far less linear. The performance of AFC effectors that rely on engine bleed air, where calibration is in terms of a momentum coefficient, will depend on flight conditions and throttle position, and may have greater non-linearity than conventional moving surfaces. General nonlinearity itself may not be an issue for modern nonlinear control techniques, but more challenging nonlinearities like control reversal can be extremely difficult to control effectively. In such cases, simply scheduling the flow to a predetermined value and coping with the transient is one solution. Another approach is to limit the control inputs to values below the reversal point. However, that potentially limits the usefulness of the effector.

With all flight control system design, the primary interest is in independent control of pitch/roll/yaw without cross-axis effects. Cross-axis effects, however, are inevitable. For example, on conventional aircraft, the rudder is required to provide the yaw moment necessary to compensate for the adverse yaw produced by ailerons during a turn. In the AVT-239 ICE configuration, the cross-axis effects were stronger than conventional control effectors, which is common for pneumatic-type control effectors (Valasek & Walchli, 1998).

Cross-axis effects can be either detrimental or advantageous to flight performance. An example of a detrimental effect occurred with the apex effectors on ICE, which were the primary yaw control effectors. These effectors also produced a nose-down pitching moment, which required additional bleed air compensation from the trailing-edge effectors. In contrast, thrust vectoring provided yaw control without a cross-axis influence on the pitching moment, and the net bleed air requirement was lower for thrust vectoring control than apex control. Examples of advantageous cross-axis effects include proverse yaw occurring with roll control and direct side force maneuvering. In the first case, when the trailing-edge control effectors were used to produce a negative roll moment (left wing down), then a negative (nose left) yaw moment was also produced, which is beneficial when making coordinated turns.

Cross-axis effects can also reveal new control opportunities. For example, the above beneficial cross-axis effects can be used to produce a direct side force on the aircraft, without a roll or pitch moment. The effect is analogous to the “MAGIC CARPET” direct lift control used by the U.S. Navy on F-18 aircraft during landing (Denham, 2016). There, direct lift control enables the aircraft to increase or decrease altitude without changing pitch angle, simplifying landing on aircraft carriers through the highly turbulent final approach region. Wind tunnel measurements with the AFCE’s on the ICE aircraft verified that superposition of midspan, apex and trailing edge control effectors with the proper amount of control authority from each would generate a relatively strong side force coefficient ($C_Y = 0.01$) without any roll moment ($C_l = 0$) and minimal yaw moment ($C_n = 8x10^{-4}$).

The potential for exploiting transient aerodynamic behaviors is still very much a basic research problem. For AFC systems, transient responses are relatively poorly understood and certainly require more detailed study to understand them sufficiently enough for design purposes. These transients are related to both the response of the AFC actuator output to input demands at the control valve, and the build-up of the aerodynamic control force/moment acting on the aircraft to the output from the AFC effector itself. These issues could be addressed by a combination of transient aerodynamic analysis combined with more detailed system response models of the embedded hardware (control valves, duct and nozzle geometry) within the aircraft.

In Section 4, we suggest that initial AFC prototypes may be hybrid aircraft that blend conventional control with AFC. In these designs, allocating control between the respective systems presents a new challenge. The control allocation function would need to optimally transition between all traditional effectors to all active flow control effectors. In the case of aircraft with over-effected actuation (i.e. more control effectors than degrees of freedom to control), a control allocation technique is required to optimally control the vehicle with minimal effort. Most methods currently used for high performance aircraft utilize algorithms that rely on linearized control effectiveness (i.e. the ‘B’ matrix) along with weighting factors that prioritize the aircraft axes to receive the most control (unstable axes typically receive the highest priority). The linear algebra algorithms at the heart of most linear control allocation functions require significant restrictions on the ‘B’ matrix to ensure mathematical tractability and prevent unrecoverable actuator saturation. This approach is applicable to both traditional effectors and flow control devices equally, from both the positive and negative sides. The methodology can be modified to make a smooth transition from traditional effectors to flow control devices or even utilize all of both types simultaneously.

Maximizing control effectiveness while minimizing flow requirements through a well-constructed CFD study and/or wind tunnel test seems like the best metric to optimize. Those studies should also focus on identification of potential nonlinearities, like sign reversals, transients and control allocation, and minimize any adverse effects when possible with proper design.

5.4 Active Flow Control System Integration

While system reliability and redundancy associated with conventional control systems are well understood from a safety and through-life support perspective, the same cannot be said for novel aircraft control approaches based on AFC technology. Further research is required to understand the factors affecting AFC reliability and redundancy and to determine robust fault tolerant architectures that allow similar probabilities of ‘loss of control’ and ‘mission abort’ as achieved when using conventional flight controls. This should cover all aspects of the AFC system architecture including redundancy/fail-safe aspects as well as maintainability of the power sources, power delivery and management and end-effectors.

With existing aircraft, a control surface requires relatively low levels of power to be moved. Aircraft control following the failure of the main engine can therefore be accommodated with emergency power generation approaches. Many AFC approaches, however, are intimately integrated with the main turbofan engine system requiring a continuous supply of pressurized air to the effectors that provide the control. In these systems, the loss of the pressurized air supply results in complete loss of control power (for both trim and maneuver). A single engine aircraft with a bleed-driven AFC system therefore potentially suffers a catastrophic loss of control if engine failure occurs. While modern single engine failure rates are exceptionally low (near zero), the question still remains about whether total loss of control is acceptable following engine failure or whether some residual control authority for a short period of time is essential to allow the aircraft to be safely ‘flown’ to an alternative abort site. This issue could be addressed by the provision of emergency sources of compressed air such as an APU or a high-pressure air tank. In addition to providing redundancy in the event of an engine failure, alternative sources of compressed air could also provide for a more flexibility and efficiency of integration. For example, an APU-driven compressor or distributed, electrically-driven, mixed-flow compressors located close to the AFC nozzles may provide a more efficient, reliable and lower weight system and help to decouple the flight control from the propulsion system allowing both to be optimized for their respective roles. These alternative architectures need to be assessed and compared to provide an understanding of their relative merits and the opportunities they provide.

The demands of the AFC system on the aircraft power generation plant (peaks of up to 3-4% of turbofan engine mass flow) have been shown to be significant but manageable and reasonable for a typical ingress mission phase. During other mission phases, such as takeoff and landing, these demands are likely to be higher and more challenging to deliver. The question then remains as to whether it is possible to deliver these increased power demands from existing propulsion systems or whether new approaches are required. For example, would new engines with the ability to operate with higher compressor bleed air demands be required, or could separate, dedicated APU-driven compressors be a viable alternative? Both these options may require compressor output for the AFC system to be continuous and sized for peak demands which then leads to questions about how to minimize overall losses by using any surplus air in an efficient manner (perhaps for propulsion). Yet another option is to implement a pneumatic accumulator tank downstream of the engine bleed-air off-take that continuously stores compressed air and can deliver higher flow rate peaks when needed, while isolating the turbofan engine compressor from surge risks due to transient flow dynamics.

Above it is suggested that early prototype implementations of AFC on a full-scale aircraft are likely to require the combination of both conventional and AFC controls to provide a means of getting development experience with acceptable reliability and safety. In many cases, the most promising AFC effectors such as TECC and YFTV occupy the same piece of aircraft real estate as the conventional control surfaces. In the case of TECC, this requires incorporation of AFC effectors within trailing edge controls with the attendant issues of getting compressed air supplies across hinges and achieving AFC end effector nozzles of compact geometry and light-weight compatible with a moving control surface. In the case of YFTV, no such requirement is needed since there are no moving control surfaces to cross inside the main engine nozzle.

The impact of implementing AFC on aircraft system initial and through-life costs (maintenance) was assessed within AVT-239 using relatively simple models based on subsystem component type, mass, complexity and location within the airframe. These methods allowed reasonable comparisons to be made against the costs of conventional control surface suites. However, parameters such as maintainability and affordability are always difficult to ascertain for systems that have yet to be fully designed, and are expected to be in service for meaningful periods of time. There is then a need to revisit such models and assessments using higher order assessment approaches, including inputs from experienced maintainability, reliability, and cost engineers to understand better the issues and impacts.

6.0 CONCLUDING REMARKS

The AVT-239 task group used the prospect of future highly contested threat environments to motivate a study on the utility of AFC effectors to provide flight control of a next generation military vehicle. The culmination of the evaluation was a trade study assessment showing that

- for flight control during an ingress/egress mission, AFC provides the required performance with a lower volume and weight relative to a conventional system,
- but, that DOD readiness levels are still low with further investment required to mature AFC technology.

Although speculation in the AFC community would see it introduced early in the vehicle design cycle, initial prototype vehicles will likely be derivatives with AFC appearing alongside conventional control approaches. This initial reality can be attributed to the many unknowns that still surround the performance and complexity of AFC effectors. In this paper, some of the challenges confronting the community have been identified and discussed including

- how to possibly re-orient the vehicle design process to create opportunities for AFC flight control,
- questions regarding the optimization of AFC effector design and placement,
- the need for new approaches to CFD in vehicle design that capture AFC performance with good fidelity,
- the unique challenges and opportunities of flight control with AFC including control non-linearities

and operation alongside a conventional system,

- and, some of the integration and reliability challenges associate with a flight control system that relies on engine bleed air and lacks performance data for long periods of operation.

Looking to the future, a newly formed group, AVT-350, will continue in the path of AVT-239, focusing on applying AFC effectors and the assessment framework to more challenging regimes of the flight envelope (e.g. take-off/landing), and gaining understanding of how AFC can impact vehicle configuration during the conceptual design stage.

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