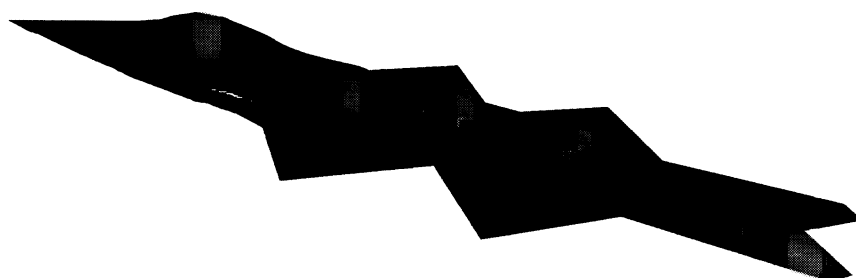




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Richard M. Wood  
NASA Langley Research Center  
Hampton, Virginia



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## A Discussion of Aerodynamic Control Effectors (ACEs) for Unmanned Air Vehicles (UAVs)

Richard M. Wood

### Abstract

A Reynolds number based, unmanned air vehicle classification structure has been developed which identifies four classes of unmanned air vehicle concepts. The four unmanned air vehicle (UAV) classes are; Micro UAV, Meso UAV, Macro UAV, and Mega UAV. In a similar fashion a labeling scheme for aerodynamic control effectors (ACE) was developed and eleven types of ACE concepts were identified. These eleven types of ACEs were laid out in a five (5) layer scheme. The final section of the paper correlated the various ACE concepts to the four UAV classes and ACE recommendations are offered for future design activities.

### Introduction

Since the early 1900s unmanned aircraft have been part of the aeronautical landscape. However, the level of interest expressed by the world community over the past decade clearly indicates that we are on the verge of a revolution in aeronautics. The guiding force behind this revolution is the dramatic advancements in electronics, microprocessors, sensors, and communication that combine to improve flight safety, performance, and situational awareness<sup>1-7</sup>

Of some concern is that aerodynamic technologies do not appear to be a significant contributor to the Unmanned Aerospace Vehicle (UAV) revolution. This observation raises several questions. Could it be that the historical constraints of manned flight have restricted the UAV designers from taking full advantage of all available aerodynamic opportunities? Or is it

simply the result of a view that aerodynamics are nothing more than a necessary evil in which the shortcomings of aerodynamics can be easily compensated by the advanced electronics? A review of the most recent literature indicates that changes are underway in the UAV community and that aerodynamic issues are receiving more attention in the design of future UAVs<sup>8-12</sup>. This change will result in a new design space for the aircraft designer and aerodynamicist, one that is unencumbered by human factor constraints, existing structural concepts, and traditional propulsion system concepts and technologies. The aerodynamicist can now utilize all that nature has to offer to create cost effective aircraft concepts that satisfy multi-disciplinary, multi-role, and multi-mission design challenges.

The expansion of the UAV design space will produce significant benefits for military UAVs. Future design activities will be able to combine a variety of conflicting performance requirements such as high survivability, extremely low drag, and hyper/super agility. For a manned aircraft design the combination of the above listed requirements typically resulted in a vehicle with a wide range of specially designed control effectors that are selectively employed in the flight envelope and result in a very complex and expensive system that would typically fall short of the performance goals. A future UAV could be designed to meet a broad spectrum of performance goals by employing advanced passive, fluidic, and unsteady ACEs that modulate both attached and separated flow and are placed in unconventional locations on the vehicle.

This paper will address a small yet significant element that influences the design of UAVs, aerodynamic control effectors. The paper will offer a review of aerodynamic control effectors (ACEs) and correlate the wide diversity of ACEs to the equally diverse number and type of UAVs, both military and civil aircraft. To help focus the arguments, the discussion will be limited to fixed wing vehicles.

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### Symbols and Nomenclature

$c$	wing chord, inches
$C_D$	drag coefficient
$C_L$	lift coefficient
$\Delta C_l$	increment in rolling moment coefficient
$C_p$	pressure coefficient
$C_y$	side force coefficient
$D$	drag force, lbf
$L$	lift force, lbf
$L/D$	lift to drag ratio
$M$	Mach number
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
$R_n$	Reynolds number
$t$	wing airfoil thickness, inches
$U_\infty$	free stream velocity, ft/sec.
$z$	vertical dimension, inches
$\alpha$	angle-of-attack, degrees

### Subscripts

$c$	wing chord
MAX	maximum

### Flight Regimes

A discussion of the flight environments for the subject vehicle class was deemed appropriate because UAVs, unlike manned vehicles, vary several orders of magnitude in size, weight, flight altitude, and speed. These geometric and operational variations result in the operational Reynolds number for UAVs to vary from  $10^2$  to greater than  $10^8$ , see figure 1<sup>13-16</sup>.

Operating at the low end of the Reynolds number scale are very small vehicles that must compete for air space with birds and insects and they must be able to manage a variety of meteorological effects such as rain and wind<sup>17</sup>. However, unlike the biological creatures, man made vehicles have not had thousands of years to evolve into efficient machines. For this reason it would be a mistake to mimic the behavior of birds and insects that have evolved, driven by the basic need to survive. Man-made vehicles operating in this realm will have much different objectives and performance goals and thus should evolve based upon the governing performance goal.

At the top end of the scale are UAVs similar in character to traditional manned type aircraft. These vehicles operate in a well-understood flight environment and they have an established evolutionary history. These aircraft have a distinct advantage over their manned cousins in that the removal of the operational and environmental limitations of man should allow for a significant expansion in the design space of UAVs.

### UAV Classification

It is unclear from the literature if the aerospace, military, or scientific community has adopted a single labeling of UAV concepts. Each of the elements of the aeronautics community has adopted various labels and monikers specific to a mission or funding source. Because of the ambiguity in the labeling of this area of research it was not possible to identify an existing labeling structure that would support the present paper as well as future fundamental aerodynamic discussions in this topic area. To resolve this issue a, Reynolds number based, structure for classifying the various UAV concepts was developed and is presented in figure 2. The objective is to classify the various UAV concepts by their flight Reynolds number and either the vehicle weight or a typical reference dimension. For this investigation, the classification is a function of Reynolds number and either span or weight, as shown in figure 2. Four classes of UAV concepts are defined using a simple labeling scheme and these are graphically depicted in figure 2. These classes are; Micro UAV, Meso UAV, Macro UAV, and Mega UAV. As one would expect there are several vehicles that appear to be exceptions to the proposed classification system, but that point is not significant for the discussion of basic technologies. However, note that the classification spaces do overlap, this reflects on the difficulty to rigidly classify this very diverse vehicle type. Note, the classification system is simply a means to organize the presentation of material and the discussion of various technologies.

A review of the information presented in figure 2 shows that a Micro UAV is any vehicle that weighs less than 1 pound and has a span under 2 feet. The definition is different than the .5 foot span and .25 pound weight coined by DARPA's

Micro Air Vehicle (MAV) label. This change to the DARPA definition was an attempt to fill in a classification void for a significant number of operational vehicles that faced the same technical challenges as that of the DARPA defined Micro Air Vehicles but were slightly larger than the DARPA definition. Note, there was consideration in adding a fifth classification of "Nano UAV" which would approximate the DARPA definition. But this idea was not viewed as acceptable because the guiding philosophy behind the classification criteria was for subject vehicles to be subjected to similar aerodynamic and environmental issues. The proposed definition scheme encompasses all vehicles that are impacted by similar technical issues. An example of a Micro UAV is the "Black Widow"<sup>18,19</sup>.

The Meso UAVs are those vehicles that are larger than the Micro category and weigh less than 2000 pounds and have less than 30 feet of wing span. Meso UAVs are typically military or experimental vehicles and the class is represented by the "Shadow"<sup>20</sup> and the "X-36"<sup>21</sup>. This class also contains nearly all of the recreational remotely piloted vehicles. While this may seem like an extremely large range in weight and span it does not reflect a broad spectrum of flight environment.

The Macro UAVs are between 2000 and 10,000 pounds and have wing span over 30 feet but less than 150 feet. This class is characterized primarily by military vehicles and will undoubtedly remain so do to the cost and complexity of developing this class of UAV. Operational Macro UAVs are "Predator"<sup>22</sup> and "X-45"<sup>21</sup>.

And the final category is the Mega UAV in which wing span exceeds 150 feet and/or the weight is greater than 10,000 pounds. At present there are only a few aircraft that can be placed into the Mega category, the "Pathfinder"<sup>19</sup> is one of the Mega UAVs and based upon wing span the "Global Hawk"<sup>23</sup> can also be placed into this category. This class of UAVs will undoubtedly remain sparsely populated with most of the future Mega UAVs being developed for either scientific purposes related to the environment or for communications.

Also noted on the figure is the characteristic flight environment for each of the four classes of UAVs. Micro UAVs operate in an environment that is defined as micrometeorology/meteorology in which the dominant issues are local and small scale wind, environmental, and atmospheric effects. A limited number of Meso UAVs also operate within the meteorology environment but for the most part they must be designed to address larger scale flight phenomena. Macro and Mega UAVs operate in the classic aerodynamic environment and as such are not affected by daily environmental occurrences.

To better understand the aerodynamic issues facing the UAV designer and thus, the operational capability of a UAV, it is important to assess the aerodynamic potential of the various UAV flight environments, see figure 3<sup>24</sup>. The graphic shows the variation in subsonic maximum lift-to-drag ratio with changes in Reynolds number for a series of single element airfoils. It is clear from figure 3 that the aerodynamic potential is a strong function of Reynolds number, or velocity, and that both Micro and Meso UAVs will be aerodynamically restricted in their flight operations. The challenge then is how to increase the aerodynamic potential and thus the performance and agility of low Reynolds number flight. Observations of nature point to various techniques used by birds and insects that increase the local velocity over the lifting surface<sup>13, 17</sup>. And even though birds and insects create the required increase in velocity by flapping and clapping their wings, the key to the problem is not flapping but the increased velocity that is created in either attached flow or vortex flow. The relationship of this issue to ACEs is that the potential of each ACE concept is a function of the aerodynamic potential of the local flow and the aerodynamic potential of the basic vehicle. This point is made clear by a review of the flow visualization photograph of figure 4 which shows a smoke-wire image for a thick airfoil at 6° angle-of-attack at a  $Rn = 40,000$ <sup>25</sup>. These data clearly show that the airfoil has massive separation and thus low energy flow that provides little aerodynamic potential for an ACE located at the wing trailing edge. Based upon the observations from figures 3 and 4, it is clear that there are a number of ACE concepts, such as fluidic devices and passive devices, which rely upon the energy in the flow field would not be applicable to Micro or Meso UAVs.

## ACE Classification

Aerodynamic control occurs when the force acting on an air vehicle surface is altered in a predetermined manner to change the vehicle dynamics. Aerodynamic control effectors (ACEs) are devices that are an integral part of an aircraft system that create a useful and controllable change in the aircraft flight behavior.

In the most simplistic form, an ACE is a moving surface (e.g. aileron) in which the magnitude of the force created is simply a function of surface area and the energy in the flow. This leads to the logical conclusion that to increase the aerodynamic control effector performance you must either increase the surface area or the energy in the flow that interacts with the ACE. These two elements are the basic premise that governs the design of all ACEs.

The present control effector design philosophy for all classes of UAVs appear to be a direct extension of that used for manned vehicles in which the ACEs are active geometric devices that move to deflect the external or internal (exhaust) flows to create the necessary aerodynamic control power. More recent research has discussed the use of micro-electro-mechanical (MEM) devices<sup>26</sup>, smart material, and other advanced materials and actuator concepts as a means to introduce advanced control authority to UAVs. While several of these flow control devices have shown promise they have not matured to a point of being available as an aerodynamic control effector<sup>27-30</sup>. And the majority of the advanced flow control concepts have not yet demonstrated the ability to generate a sufficient change in the aerodynamic forces acting on a vehicle to be viewed as an ACE. Hence, these types of devices will not be discussed in the present paper.

When issues related to military vehicles are considered a number of concerns are raised. One of the primary concerns is that moving sensor-visible elements on an aircraft to create control power is counter to the design constraints imposed by reduced cost and improved survivability. It may be argued that moving external surfaces of a vehicle to create aerodynamic control is also counter to achieving low drag. In a first order analysis, the purchase

cost and operational cost of an aircraft is directly proportional to the number of parts of an aircraft.

For military vehicles survivability is directly proportional to the number and types of physical breaks and curvature breaks in the sensor-visible surfaces. Aerodynamic drag is also proportional to the number of breaks in the external surfaces of a vehicle. Eliminating moving control effectors will reduce the number of parts, reduce the breaks in the surface, and reduce the breaks in the surface curvature and thus, cost will decrease, survivability will increase and drag will decrease.

## Labeling Scheme

The first step in discussing aerodynamic control effectors is to define a labeling scheme that will support known ACE types/concepts. Presented in figure 5 is a proposed five (5) layer scheme utilized in the present paper. Note, the dashed lines in the figure indicate that the multi-layer labeling scheme presented for the active, geometric, steady, and attached flow ACE branches is the same for the passive, fluidic, unsteady, and separated flow branches.

The first layer is used to differentiate between passive (P) and active (A) effectors where an active device requires the addition of energy to cause an aerodynamic change. The passive device does not require energy to be added to the system but instead works with the naturally changing energy state of the flow field.

The second layer identifies the effector as a geometric (G) device or a fluidic (F) device. For the present discussion, geometric devices are ones that move a portion of the external surface of a vehicle and a fluidic device adds or subtracts (i.e. blows or sucks) air into or out of the external flow.

The third layer differentiates between a steady (S) or unsteady (U) device (i.e. varies with time about a nominal setting). A traditional flap system that is simply changing position to create a series of steady state conditions would not be an unsteady device.

The fourth layer differentiates between attached (AT) or separated (SE) flow as the mechanism that causes a change in the aerodynamics.

Examples would be a traditional flap system and a vortex flap system, respectively.

The final and fifth layer is related to the force vector that is modified by the ACE. While most ACEs operate on both the lift and drag (L/D) forces some devices work only the lift (L) or the drag (D) forces.

An example label for a traditional flap system would be:

A – active, driven by an actuator  
 G – geometric device  
 S – steady state flow conditions is the goal  
 AT – attached flow is the goal  
 LD – changes both the lift and drag forces

To present the diversity of ACE concepts and help explain the labeling scheme, examples of the eleven ACE types representing the five layers discussed above are presented in figures 6 through 10.

### ACE Examples

Presented in figure 6 are examples of active and passive ACE concepts<sup>31-34</sup>. The two active concepts are shown on the left of the figure and the two passive concepts are shown on the right. The four examples shown can be further classified in accordance with the proposed ACE labeling scheme as geometric and fluidic. The figure shows that there are two concepts that are geometric with separated flow (see the top of the figure) and two concepts that are fluidic with attached flow (see bottom of figure). The two geometric devices shown at the top of the figure are simple devices and may require minimal volume and therefore can be applied to all four UAV types. However, the two fluidic devices shown at the bottom of the figure are complex concepts and may require significant volume and thus it is suggested that they be applied only to Macro and Mega UAVs.

Examples of geometric and fluidic ACE concepts are presented in figure 7<sup>33, 35-37</sup>. All of the concepts presented in this figure employ separated flow to produce the desired aerodynamic control. The two geometric concepts on the left side of the figure are active devices with the concept on the bottom being an unsteady ACE and the concept on the top being a steady ACE. The two concepts on the right side

of the figure both use fluidics to control the aerodynamic forces on the forebody yet they differ in that the ACE shown on the bottom of the figure is a passive device and the concept shown on the top of the figure is an active device. As previously discussed for figure 6 the top left device can be applied to all UAV types. The other three ACE concepts shown in figure 7 can be considered for all UAV types with the exception of the Micro UAV. The exclusion of the Micro UAV class from using these three concepts is primarily based upon either the volumetric or energy requirements of these ACE concepts.

Steady and unsteady<sup>38</sup> attached flow ACE concepts are depicted in figure 8. The steady concept is the traditional flap system that may be leading-edge only, trailing-edge only, or a combination of leading and trailing-edge flaps. These devices, while in continual motion, are not unsteady devices because the motion itself is not used to create an aerodynamic control force. In contrast, the rotating cylinders concept, unsteady ACE (shown on the right) rely upon the rotational motion to control the attached flow over the airfoil and thus control the aerodynamic loading and control force. It is suggested that application of the rotating cylinder ACE be limited to Macro and Mega UAVs because of complexity, weight, volume, and power requirement issues. However, as discussed previously, the traditional flap system will remain the primary ACE for all sizes of non-military UAVs.

The next concepts to be discussed are the separated flow<sup>34,39</sup> and attached flow<sup>40,41</sup> ACEs, (see figure 9). Attached flow ACE concepts are shown on the left side of the figure and separated flow ACE concepts are shown on the right side of the figure. These four concepts are further divided with the concepts at the top of the figure being active, fluidic ACE and the two concepts at the bottom of the figure are passive, geometric ACE. Application of the active concepts would be limited to the Macro and Mega UAVs because of the energy requirements for operation. It is expected that the two passive concepts shown in the figure can be used on all UAVs because of the negligible volumetric requirements.

The final grouping of concepts relate to the force vector that is modified to create the desired control force<sup>35,42-44</sup>. Shown in figure 10 are the

lift, drag, and lift/drag force vector ACE concepts. An example of a lift vector ACE is shown on the right side of the figure and is represented by vehicle planforms. The lifting surface planform can be considered a first order control effector. A properly selected planform can provide the potential for a significant improvement in control authority by conditioning and controlling the vehicle flow field throughout the flight envelope. An example would be the generation of coherent vortex structures that persist over a broad range of lift conditions and Mach numbers.

The depicted lift ACEs are passive, geometric, attached flow/separated flow concepts. Drag and lift/drag ACE concepts are shown on the left side of the figure. Drag force ACE is an active, geometric, steady, separated flow concept that utilizes inflatable bumps to increase the drag an order of magnitude. The lift/drag ACE concept is a novel vortex flap that is an active, geometric, steady, separated flow ACE. It is suggested to limit the application of drag and lift/drag ACE concepts to Macro and Mega UAVs because they operate in a high aerodynamic potential environment. The example lift ACE concept shown is applicable to all UAVs.

The remaining sections of this paper will review the full range of ACE concepts and correlate these concepts to the unique requirements and flight environments of the various classes of UAVs.

### ACE to UAV Matching

To determine the availability of each of the eleven ACE types (i.e. A, P, G, F, ..... ) to be integrated into each of the four UAV classes it is important to review the complexity and requirements of each ACE type, the UAV class design requirements, and the operational environment of each UAV class.

An assessment of the technical maturity of the eleven ACE types is presented in figure 11. The scale for technical maturity is labeled low to high to reflect this subjective assessment. This assessment of the 11 ACE types shows that the active, geometric, steady, attached, and lift/drag ACE concepts are the most mature and are applicable to each UAV class. The passive, fluidic, unsteady, and drag devices are the least mature and thus, should only be considered for

UAVs that could afford the development, operational, and maintenance cost associated with these devices. And falling between the two groups discussed above are the separated and lift ACE concepts.

A review of some factors that should be considered in the selection of an ACE are related to the design requirements of the UAV class, as discussed below. A first order analysis of the UAV design environment indicates that; the percent available volume and weight for ACEs is reduced with reduced UAV size. In contrast, the ACE effectiveness and robustness must increase with decreasing UAV size. This requirement is a result of the low Reynolds number flow (i.e. low energy) and significant meteorological phenomena that dominate the Micro and Meso UAVs flight environment. Other factors are the cost and complexity of the ACE must reduce with reducing UAV size. And the final point is that the aerodynamic potential of an ACE will reduce with reducing UAV size. An assessment of these issues indicates that specific types of ACEs should only be used on specific size UAVs. A graphical representation of this subjective assessment is presented in figure 12.

The matrix presented in figure 12 correlates the eleven ACE types to the four UAV classes and may be thought of as a design/opportunity matrix for preliminary design of future UAVs. Based upon the author's subjective evaluations the following observations are offered. The chart shows that Micro UAVs should avoid the use of fluidic, unsteady, and drag ACE concepts because of the complexity and volume requirements of the concepts. Drag ACE concepts should be avoided because Micro UAVs operate within a low aerodynamic potential environment. Passive ACE concepts are only suggested in the form of advanced planform and airfoil shapes.

Meso UAVs should avoid unsteady and drag ACE concepts. And Mega UAVs should avoid unsteady, separated, and drag ACE concepts.

The Macro class of UAV can utilize all eleven types of ACE concepts. This recommendation reflects the fact that Macro UAVs are the most technically complex vehicles that would be built and thus, might better afford the development cost for any desirable ACE concept.



## Aerodynamic and Stability Augmentation

Even with the diversity of ACE concepts available to the designer there may be situations in which there is a need to augment the effectiveness of the ACE concept by augmenting the aerodynamic potential of the flow environment or by augmenting the stability of the vehicle.

Presented in figure 13 are several concepts<sup>10, 36</sup> to augment the aerodynamic potential of ACE concepts and presented in figure 14 is a chart that reflects the applicability of the aerodynamic augmentation (AA) concept to each UAV class.

The three aerodynamic augmentation concepts presented in figure 13 are; vortex flow<sup>10</sup> interactions, propeller thrust interactions<sup>10</sup> and flow dynamics<sup>36</sup>. Each of these three concepts increase the energy level of the flow field over the vehicle. The vortex flow and thrust concepts are steady flow devices that work by increasing the velocity of the flow passing over the ACE concept. Whereas the flow dynamics concept sets up a fluctuating velocity and pressure field that interacts with an ACE concept to increase the effectiveness of the ACE.

The correlation of these concepts to the four UAV classes is presented in figure 14. As discussed previously, the Micro and Meso class UAVs operate in an environment with low aerodynamic potential and as a result they would benefit greatly from any form of aerodynamic augmentation. However, they are likely precluded from using a flow dynamics concept due to the complexity, volume requirements, and cost. The vortex flows and thrust interaction concepts require the placement of ACE concepts in locations that allow them to take advantage of the interacting flow field.

Macro and Mega UAVs operate in an environment with high aerodynamic potential and would not normally require any form of augmentation. However there may be off design conditions, such as take off and landing, that a small dynamic flow device may benefit performance.

The next topic to discuss is stability augmentation (SA). Stability augmentation is a well established discipline within the community and the existing systems and capabilities are clearly applicable to most UAVs. However, the

Micro UAV class may not be able to take advantage of the existing capabilities due to the limited options in vehicle design and ACE concepts. The discussion of stability augmentation will focus on Micro UAVs in an effort to offer some unconventional geometric approaches to the problem.

Presented in figure 15 are two geometric based stability augmentation systems for Micro UAVs. Depicted at the top of the figure is a passive aero elastic wing concept which attempts to mimic the wing warping of a bird<sup>12</sup>. This concept has shown significant promise and remains under development. The results to date show benefits for small-scale and low-energy atmospheric instabilities but the ability of the system to manage large-scale atmospheric instabilities has yet to be demonstrated.

The second concept is a passive mass system that deploys after launch and is simply a means to increase the moment of inertia of the system. The mass pod would house the heavy and large-volume power and optic systems. This concept should allow for Micro UAV operation in large-scale atmospheric instabilities.

The previous discussion identified a number of ACE concepts, aerodynamic augmentation concepts, and stability augmentation concepts for the UAV community. The final section of the paper will discuss and recommend ACE, AA, and SA concepts for each of the UAV classes.

## UAV Recommendations

The following discussion will provide examples of planform and ACE concepts for each UAV class. In addition an expanded discussion will be presented for the Macro class of UAV in order to provide the reader additional context for several advanced ACE concepts.

### Micro UAV

Micro UAV design is a unique challenge that has and continues to produce innovative designs and technologies. In addition to the unique size requirement, the vehicles must operate in a completely foreign environment that until recently has only been occupied by biological creatures. It is recognized that we must learn

from the birds and bees but we must not mimic their behavior because they are a result of the fight for survival and other environmental factors that we do not understand.

In developing a suite of ACE concepts for Micro UAVs one should begin with the planform. Due to the current limitations in propulsion options and available power sources Micro UAVs will be relegated to low speed, low altitude flight with a propeller providing the thrust. For this type of vehicle the preferred planform characteristics evolve to long chords with a low to moderate sweep and aspect ratio (AR) as the span of the vehicles decreases in size. This trend is simply a means to maximize the lifting surface of the vehicle. A benefit of these planform shapes is that they allow for the generation of significant vortex flow at the tips, which provides much needed lift, see left side of figure 16. Additional control augmentation can be achieved by locating the ACE concepts in the slip stream of the propeller thrust and tip vortices. It is also suggested that the proposed passive mass stability augmentation system be employed.

Depicted on the right of the figure are several ACE concepts that are applicable to Micro UAVs. Shown at the top-right of the figure is an active flying tip concept, which would integrate well into the vehicle concept depicted on the top-left. The middle concept is a traditional flap system that may use advanced materials for actuation. To enhance the performance of the flap it should be positioned within either the propeller or vortex streams. The final example is the use of advanced airfoil shapes that have been shown to increase the lift by more than 30%<sup>40</sup>.

### Meso UAV

Meso UAV designs can also be very diverse as reflected in the two radically different shapes shown on the left in figure 17. These vehicles may take the classic shape of wing, tail, and fuselage as represented by the Shadow or may appear more exotic, as represented by the X-36. The X36 vehicle is representative of the sophistication you would find more consistently in the Macro UAV class. This diversity in shapes reflects the diversity in the mission requirements of the two vehicles and the influence of the flight environment.

Similar to the Micro UAV class, selection of the planform shape would be the first step in developing a suite of ACE concepts for Meso UAVs. Unlike the Micro UAV there is not a limitation in propulsion options and available power sources for Meso UAVs. Meso UAVs operate over a broad range of speeds and altitudes. For this type of vehicle, the preferred planform characteristics are primarily a function of speed and mission. Although control augmentation can be used in a manner similar to Micro UAVs it is typically not required due to the increased speed of the vehicles.

Depicted on the right of the figure are several ACE concepts that are applicable to Meso UAVs. Shown at the top-right of the figure is an active fluidic concept that uses micro blowing to control vortex formation. This concept would integrate well into the X36 vehicle concept to provide directional stability and control. The second ACE concept is a traditional flap system that may use advanced materials for actuation in order to reduce volume and weight. The final example is the use of advanced planform shapes. The planforms depicted have been shown to increase lift by more than 30%. It is recommended that multiple lifting surfaces be used to distribute the lift vector and provide additional opportunity to improve control authority of ACE concepts.

### Macro UAV

Macro UAV designs are primarily military vehicles with a significant diversity in shape and performance as reflected in the two radically different shapes shown on the left in figure 18. All of these vehicles are extremely sophisticated systems with multi mission performance factored into their design. Although these vehicles are all very complex they still take on dramatically different shapes; from the classic wing, tail, fuselage as represented by the Predator, to the exotic tailless X-45 concept. This diversity in shapes reflects the diversity in the mission requirements of the two vehicles.

Critical ACE concepts for Macro UAVs include the vehicle planform shape. The Macro UAVs are similar to the Meso UAVs in the propulsion options and available power sources. Macro UAVs operate over a broad range of speeds and at altitudes beyond those for Meso UAVs. For this type of vehicle the preferred planform

characteristics are primarily a function of speed and mission. ACE aerodynamic augmentation is not required due to the increased speed of the vehicles.

Depicted on the right of the figure 18 are several ACE concepts that are applicable to Macro UAVs. Shown at the bottom-right of the figure is passive porosity, a passive fluidic concept that can be applied to a fuselage or a wing to provide all axis control without any breaks in the external surface. The second ACE concept is micro-drag generators. These are active, geometric, and inflatable devices that may make use of advanced materials for actuation. The final example is the use of advanced multiple lifting surface planform shapes that have been shown to increase the lift by more than 30%.

Additional discussion of each of the three ACE concepts shown in figure 18 are presented in figures 19 through 22. The author selected these three ACE concepts for expanded discussion because of the author's familiarity with the material. Note, these are offered as examples of advanced ACE concepts.

### Passive Porosity Technology

The passive porosity technology has been extensively studied both experimentally and computationally as a means to control shock/boundary layer interaction to control the forces and moments of vehicles<sup>31, 35, 44-46, 48</sup>.

Passive porosity is designed to modify and control the pressure loading acting on a surface. The passive porosity concept consists of a porous outer surface and a solid inner surface. The volume between the outer and inner surfaces form an open plenum that is filled with the same fluid that is flowing over the exterior surface of the porous skin. The effectiveness of the concept is dependent upon the ability of the system to allow unrestricted communication between large pressure differences on the external surface (high permeability).

The passive porosity effector can be configured as a semi-active ACE by providing a means to control the permeability of the porosity. The means to activate and deactivate the passive porosity system may be accomplished by reducing the permeability of the porous surface

or by reducing the permeability of the plenum. The porous surface permeability may be controlled by restricting the size of or closing the passages through the porous surface with a smart skin technology or by covering the internal surface of the porous surface with a non porous surface or low permeability surface. The permeability of the passive porosity system may also be controlled by changing the plenum characteristics.

Figure 19 presents side force data for a porous 5.0 caliber, tangent-ogive forebody model with various circumferential extents of porosity, a porous forebody with chine, and the F/A-18 HARV with actuated strakes. Also shown on the figure is the available side force from the F/A-18 vertical tail. In the region where asymmetric vortex shedding and asymmetric side force generation typically occurs for a solid forebody ( $\alpha > 20^\circ$ ), the application of  $360^\circ$  of porosity eliminates the asymmetric vortex loading. Application of porosity to the left side of the forebody allows for maximum control of the side force. The addition of a chine to the same model increases the side force contribution of passive porosity. A comparison of the generated forebody forces shows significant increases at angles-of-attack greater than  $25^\circ$  over that available with more traditional movable control effectors, a vertical tail or actuated forebody strakes.

Representative passive porosity control effector results at a Mach number of 0.17 for a  $65^\circ$  Delta wing model are presented in figure 20. Simply for comparison purposes, the representative control effectiveness data for the F/A-18 aircraft is also shown in figure 20. Roll control for various extents of tip porosity is shown in the figure. The data are for configurations with porosity applied to both the upper and lower surface. This application of porosity allows the passive porosity system to eliminate (dump) lift on a particular region of a wing. The data of figure 20 clearly show that significant control authority is available with this technology, at moderate angles-of-attack. At angles-of-attack greater than  $10^\circ$  a comparison of the passive porosity results with those for the conventional aerodynamic control effector show that the passive porosity device is more effective. At angles-of-attack below  $10^\circ$  the conventional aerodynamic control effector is more effective.

### Micro-Drag Generators (MDGs)

The Micro Drag Generator concept<sup>47</sup> uses small deployable devices referred to as MDGs that individually generate small amounts of drag, but when deployed in large numbers can generate substantial amounts of drag. The micro-drag generators (MDGs) may be thought of as miniature spoilers or speed brakes. During normal operation of the vehicle (e.g., during cruise), the devices would not be extended into the flowfield and would not increase the drag of the vehicle.

MDGs are designed to force the flow on a vehicle to separate on the aft-facing side of the device and to reattach before reaching the next device, see figure 21. Note that the MDG devices tested were sized for wind-tunnel conditions (i.e. thicker boundary layers exist in the wind tunnel than would be seen in flight for the same wing chord) to ensure the concept was properly evaluated. The MDG concept allows substantial amounts of drag to be generated with a simple system of small devices. The drag generated by a system of MDGs is expected to be equivalent to that generated from a single device with the same projected area as the sum of all the MDG projected areas.

MDGs were experimentally investigated on the right hand side of a high aspect ratio wing with the GA(W)-1 airfoil, see figure 21. The wind-tunnel data indicated that the deployment of MDGs on a wing can increase the drag by as much as 400% (medium density, large drag plates), see figure 21. The 300-400% increase in wing drag equates to a change in drag coefficient between the clean wing and the wing with MDGs of 0.04 to 0.11.

These results indicate that by asymmetrically deploying MDGs (only on one wing panel) on an aircraft, substantial amounts of control effectiveness (yawing-moment coefficients) may be generated. Therefore, MDGs appear to be an effective concept for decelerating or controlling a vehicle.

### Planform Technologies

As mentioned previously, the planform may be viewed as a primary contributor to control

effector performance<sup>43,44</sup> by energizing the flow field passing over the vehicle. Selection of a planform should consider concepts that would provide significant increases in lift and linear stability characteristics for angles-of-attack up to 70°. A review of the study reported in reference 35 shows that a total of 21 planforms were investigated. The planform types were a diamond (baseline configuration), twin-body, sawtooth forebody, twin-wing, cut-out wing, and joined wing.

The data of figure 22 show that the sawtooth forebody concept provides a significant increase in lift for all angles-of-attack greater than 10°. The data also show that the sawtooth forebody concept provides a 25% increase in maximum lift over the baseline planform. Note, the magnitude of these benefits is depressed by the use of the total planform area as the reference area for data reduction. The benefit achieved by the sawtooth forebody concept results from both vortex lift acting on the sawteeth as well as the parent wing and an interfering flow field emanating from the sawteeth onto the parent wing. The interfering flow field is characterized by a downwash field that acts on the parent wing. This allows the parent wing to operate at an effective lower angle of attack thereby reducing separation. It is important to note that the sawtooth forebody concept has been shown to be applicable to other planform shapes.

The data of figure 23 show that the twin wing concept also provides a significant increase in lift starting at 20° angle-of-attack and extending to 70° angle-of-attack. The data show that the twin wing concept also provides a 25% increase in maximum lift over the baseline planform. It is conjectured that the benefit achieved by the twin wing concept results from reduced flow separation on the aft wing due to a strong downwash field from the forward wing. This downwash allows the aft wing to operate at an effective lower angle of attack thereby reducing separation. It is important to note that the multiple wing concept has been shown to be applicable to other planform shapes.

These data show that the high-lift performance of aircraft can be greatly enhanced through the use of multiple primary lifting surfaces and interfering flow fields.

## Mega UAV

Mega UAV designs are either military vehicles or scientific vehicles that are one of a kind or may see limited production. The very specialized mission of these concepts results in very unique shapes as reflected in the two radically different designs shown on the left in figure 24. As with the Meso and Macro UAV classes, these very complex vehicles may vary significantly in shape; from the classic shape of wing, tail, and fuselage as represented by the Global Hawk to the all-wing Pathfinder. Despite the apparent diversity in shape, these two vehicles rely upon the same classic airfoil performance design criteria to achieve their objectives.

Because the design of these vehicles rely heavily on classic airfoil performance, the example ACE concepts to be presented for Mega UAVs will focus on those that are airfoil based. To date Mega UAVs operate over a limited range of speeds and altitudes as a result the preferred planform is low sweep and high aspect ratio. Because of the high aspect ratio planforms, aero elastic tailoring is typically used.

Depicted on the right of the figure are several ACE concepts that are applicable to Mega UAVs. The first ACE concept is a traditional flap system that may use advanced materials for actuation, see top-right. Shown at the bottom-right of the figure is passive porosity, a passive fluidic concept that would be applied to the wing to provide low drag control authority by minimizing breaks in the external surface.

## Concluding Remarks

The paper has discussed a small yet significant element that influences the design of UAVs, aerodynamic control effectors. Eleven types of aerodynamic control effectors (ACEs) were identified and correlated to the wide diversity and type of UAVs.

A Reynolds number based, UAV classification structure was developed and is presented. The UAV classification scheme was developed in order to classify the various UAV concepts by their flight Reynolds number and either the

vehicle weight or a typical reference dimension. Four classes of UAV concepts were defined using a simple labeling scheme and these are; Micro UAV, Meso UAV, Macro UAV, and Mega UAV.

In a similar fashion a labeling scheme for aerodynamic control effectors was developed and eleven types of ACE concepts were identified. These eleven types of ACEs were laid out in a five (5) layer scheme for the present paper. The types of ACE concepts were; active, passive, geometric, fluidic, steady, unsteady, attached flow, separated flow, lift force, drag force, and lift/drag force. A correlation and recommendation of ACE concepts to each UAV class was presented to provide design guidance to the community.

The consideration of all types of ACE concepts in the design of future UAVs will expand the design space allowing future UAVs to be developed that meet a broad spectrum of performance goals unattainable in manned flight.

## References

1. Unmanned Aerial Vehicles: DoD's Demonstration Approach has Improved Project Outcomes. Aug. 1999.
2. Swift, G. A., Shepard, C., and Sebek, K.: Subsonic Unmanned Air reconnaissance System Design. AIAA Paper 90-3281, 1990.
3. VanDyke, W. A., Thomas, C., and Killion, T.: Joint Unmanned Aerial Vehicle Family Interoperability and Commonality. AIAA 90-3249, 1990.
4. Cleaver, C. M.: Development of an Unmanned Air Research vehicle for Supermanueverability Studies. Naval Post Graduate School, AD-A227165, 1990.
5. System Design Considerations for Unmanned Tactical Aircraft (UTA). AGARD-CP-594, 1998.

6. Rolfe, D., Dawydoff, A., Winter, W., Byshyn, W., and Clark, H; Airplanes of the World, 1490 to 1969. Simon and Schuster. 1969.
7. Taylor, M. and Mondey, D.; Guinness Book of Aircraft Facts and Feats. Guinness. 1984.
8. Munday, D. and Jacob, J. D.; Flow Control Experiments for Low Re Adaptive Airfoils. AIAA 2000-0654, 2000.
9. Munday, D. and Jacob, J.; Active Control of Separation On a Wing with Conformal Camber. AIAA 2001-0293, 2001.
10. Gursul, I., Taylor, G., and Wooding, C. L.; Vortex Flows Over Fixed-Wing Micro Air Vehicles. AIAA 2002-0698, 2002.
11. Gad-el-Hak, M.; Micro-Air-Vehicles: Can They Be Controlled Better. J. of Aircraft, Vol. 38, No. 3, June 2001, pp.419-429.
12. Waszak, M. R. and Jenkins, L. N.; Stability and Control Properties of an Aeroelastic Fixed Wing Micro Aerial Vehicle. AIAA 2001-4005, 2001.
13. Allen, J. E.; Aerodynamics: The Science of Air in Motion. McGraw Hill Book Co. 1982.
14. Gault, D.; Boundary Layer and Stalling Characteristics of the NACA 63-009 Airfoil Sections. NACA TN 3524, 1955.
15. Chappell, P. C.; Flow Separations and Stalling Characteristics of Plane, Constant-Section Wings in Subcritical Flow. J. Royal Aeronautical Society, Vol. 22, No. 685, pp. 82-90, 1968.
16. Mueller, T. J.; Aerodynamic Measurements at Low Reynolds Numbers for Fixed Wing Micro-Air Vehicles. RTO AVT/VKI Special Course on Development and Operation of UAVs for Military and Civil Applications. Sept. 13-17, 1999, VKI, Belgium.
17. Anders, J. B.; Biomimetic Flow Control. AIAA 2000-2543. 2000.
18. Grasmeyer, J. M. and Keenon, M. T.; Development of the Black Widow Micro Air Vehicle. AIAA 2001-0127, 2001.
19. [www.aerovironment.com](http://www.aerovironment.com), May 2002.
20. [www.aaicorp.com](http://www.aaicorp.com), May 2002.
21. [www.boeing.com](http://www.boeing.com), May 2002.
22. [www.ga.com/asi/aero.html](http://www.ga.com/asi/aero.html), May 2002.
23. [www.tdryan.com](http://www.tdryan.com), May 2002.
24. McMaster, J. H. and Henderson, M. L.; Low Speed Single Element Airfoil Synthesis. Technical Soaring, Vol. 6, 1980, pp. 1-21.
25. Mueller, T. J. and Batill, S. M.; Experimental Studies of Separation on a Two-Dimensional Airfoil at Low Reynolds Number. AIAA Journal, Vol. 20, No. 4, April 1982, pp.457-463.
26. Loth, E.; Smart Mesoflaps for Control of Shock Boundary Layer Interaction. AIAA 2000-2476, 2000.
27. Emerging Techniques in Drag Reduction, edited by Choi, K. S., Prasad, K. K., and Truong, T. V.; Mechanical Engr. Pub. Ltd., London, 1996.

28. Sellin, R. H. J. and Moses, R. T.: Drag Reduction in Fluid Flows: Techniques for Friction Control. Ellis Horwood Ltd. Chichester, 1989.
29. Bechert, D. W., Bruse, M., Hage, W., VanderHoeven, J. G. T., and Hoppe, G.: Experiments on Drag-Reducing Surfaces and their Optimization with an Adjustable Geometry. *Journal of Fluid Mechanics*, Vol. No. 338, pp. 59-87, May 1997.
30. Gad-el-Hak, M. and Bushnell, D.: Status and Outlook of Flow Separation Control. AIAA 91-0037, 1991.
31. Nagamatsu, H. T. and Orozco, R. D.: Porosity Effect on Supercritical Airfoil Drag Reduction by Shock Wave Boundary Layer Control. AIAA-84-1682.
32. Maksoud, T. M. A., Al-Shihry, A., and Wood, J.: Theoretical/Experimental Analysis of a Novel Airbreathing Device for Flow Control. *J. of Aircraft*, Vol. 38, No. 1, Feb. 2001, pp. 28-35.
33. Barnard, R. H.: Evaluation of Low-Speed Handling and Direct Lift Control Characteristics of a Wing with Collectively Variable Incidence Wing Tip Elements. ICAS-94-4.3.2. 1994.
34. Bamesfeld, G. and Maughmer, M. D.: Experimental Investigation of Self Actuating, Upper-Surface, High-Lift-Enhancing Effector. *J. of Aircraft*, Vol. 39, No. 1, Feb 2002, pp. 120-124.
35. Wood, R. M. and Bauer, S. X. S.: Advanced Aerodynamic Control Effectors. SAE 1999-01-5619, 1999.
36. Lang, J. D. and Francis, M. S.: Interaction of a Oscillating Control Surface with an Unsteady Separation Region. *J. of Aircraft*, Vol. 13, No. 9, Sept, 1976, pp. 687-694.
37. Roos, F. W.: Microblowing for High-Angle-of-Attack Vortex Flow Control on a Fighter Aircraft. AIAA 96-0543.
38. Modi, V. J.: On The Moving Surface Boundary-Layer Control. AIAA 2000-2238, 2000.
39. Walchli, L. A. and Langam, K. J.: Transonic Evaluation of a Pneumatic Spoiler for Aircraft Control. AIAA 99-3194, 1999.
40. Eggers, A. J. Jr.: Aerodynamic Characteristics at Subcritical Mach Numbers of Two Airfoil Sections Having Sharp Leading Edges and Extreme Rearward Position of Maximum Thickness. NACA RM No. A7C10, Nov. 1947
41. Schlichting, H., Truckenbrodt, E., and Ramm, H. J.: Aerodynamics of the Airplane. Mc-Graw Hill International Book Company, 1979.
42. Mattick, A. A. and Stollery, J. L.: Increasing the Lift:Drag Ratio of a Flat Delta Wing. *Aeronautical Journal*, Oct. 1981, pp. 379-386.
43. Gatlin, G. M. and Nuehart, D. H.: Water Tunnel Flow Visualization Study Through Poststall of 12 Novel Planform Shapes. NASA TM 4663. March 1996.
44. Gatlin, G. M. and McGrath, B. E.: Low-Speed Longitudinal Aerodynamic Characteristics Through Poststall for Twenty-One Novel Planform Shapes. NASA TP 3503. August 1995.
45. Wood, R. M., Banks, D. W., and Bauer, S. X. S.: Assessment of Passive Porosity with Free and Fixed Separation on a Tangent Ogive Forebody. AIAA-92-4494, 1992.

46. Bauer, S. X. S. and Hemsch, M. J.: Alleviation of Side Force on Tangent Ogive Forebodies Using Passive Porosity, Proposed AIAA Paper 10th Applied Aerodynamics Conference, June 1992.
47. Wilcox, F. J.: Experimental Investigation of the Effects of a Porous Floor on Cavity Flow Fields at Supersonic Speeds. NASA TP 3032, 1990.
48. Bauer, S. X. S.; An Aerodynamic Assessment of Micro-Drag Generators (MDGs). 16<sup>th</sup> AIAA Applied Aerodynamics Conference. AIAA-98-2621.
49. Hunter, C. A., Viken, S. A., Wood, R. M., and Bauer, S. X. S.; Advanced Aerodynamic Design of Passive Porosity Control Effectors. AIAA 2001-0249, 2001



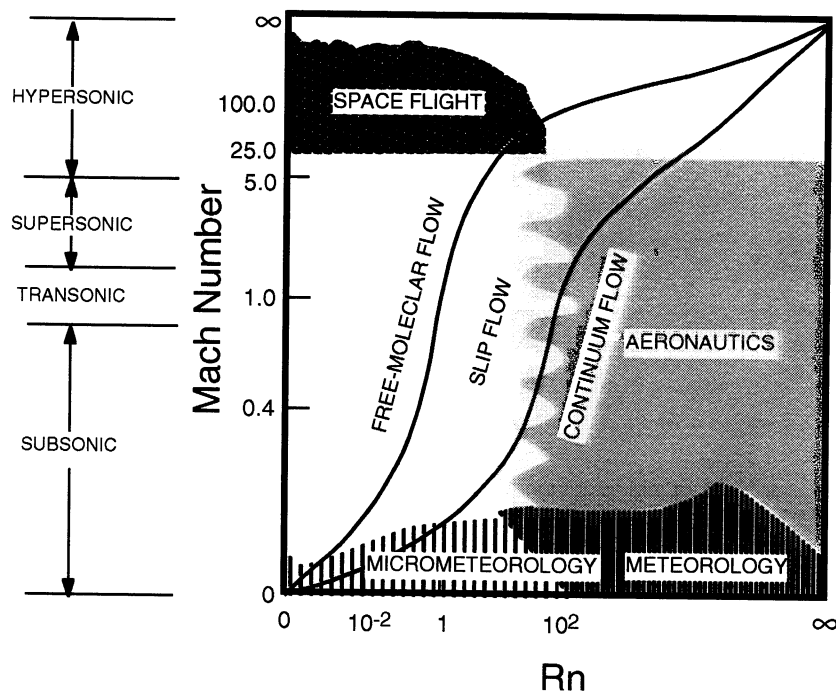


Figure 1. Aerodynamic flight regimes. Ref. 13.

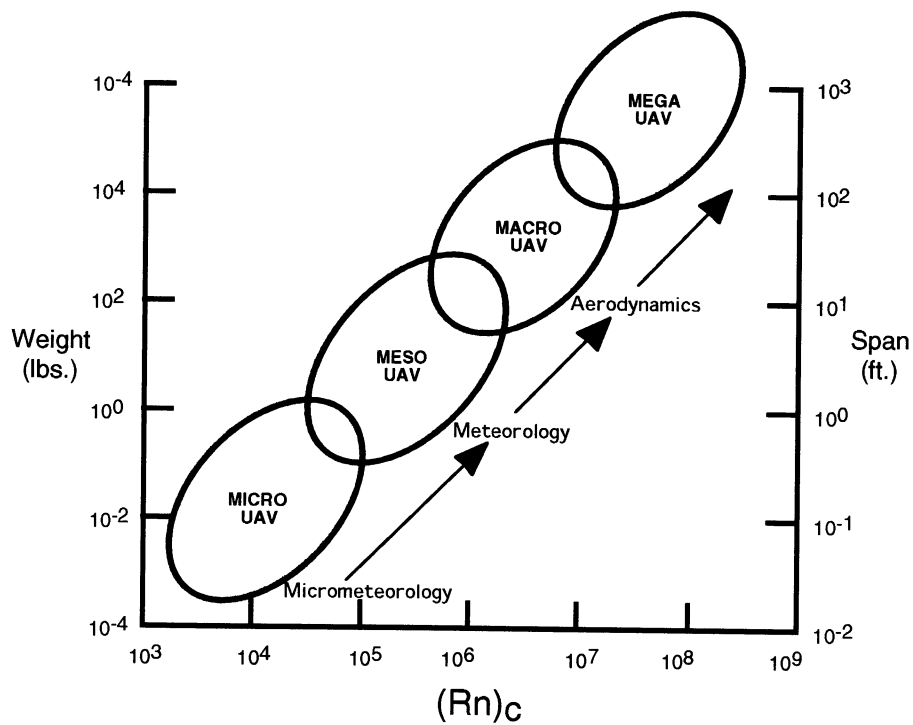


Figure 2. UAV classification chart as a function of wing chord Reynolds number and vehicle geometry.

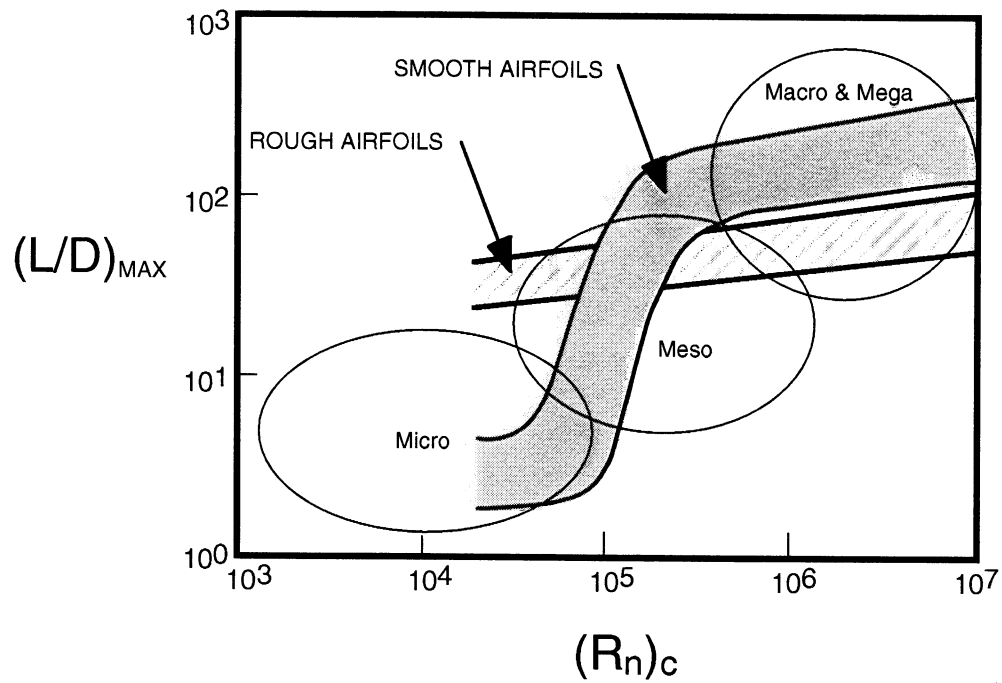


Figure 3. Aerodynamic performance of single element airfoils at low speed. Ref. 24.

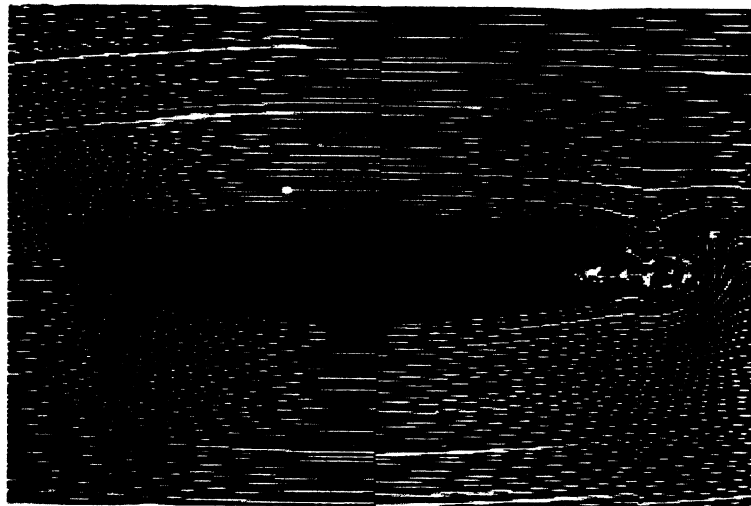
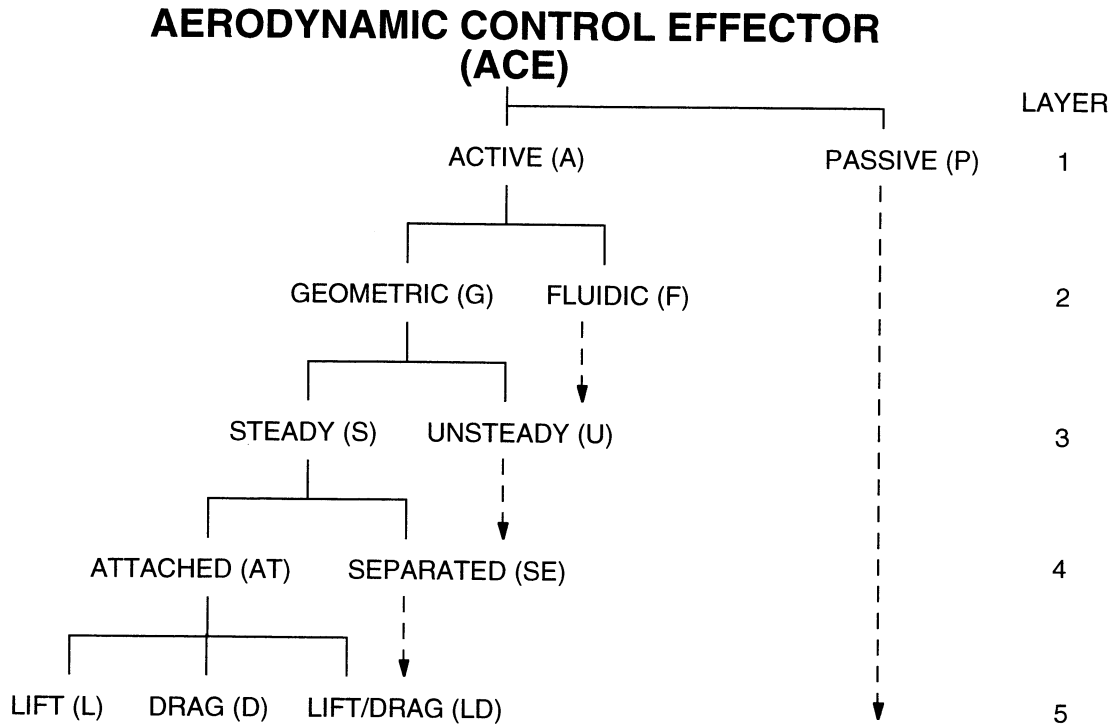


Figure 4. Smoker wire flow visualization for a smooth NACA 663-018 airfoil at 6° angle-of-attack at a  $R_n = 40,000$ . Ref. 25.



ACTIVE (A)	aerodynamic change requires energy addition
PASSIVE (P)	aerodynamic change does not require energy addition
GEOMETRIC (G)	aerodynamic change induced by movement of external geometry
FLUIDIC (F)	aerodynamic change induced by addition or subtraction of external fluid
STEADY (S)	aerodynamic change mechanism is invariant with time
UNSTEADY (U)	aerodynamic change mechanism varies with time
ATTACHED (AT)	aerodynamic change mechanism is attached flow
SEPARATED (SE)	aerodynamic change mechanism is separated flow
LIFT (L)	aerodynamic change mechanism modifies the lift vector
DRAG (D)	aerodynamic change mechanism modifies the drag vector
LIFT/DRAG (LD)	aerodynamic change mechanism modifies both the lift and drag vectors

Figure 5. Aerodynamic control effector definition and labeling scheme.

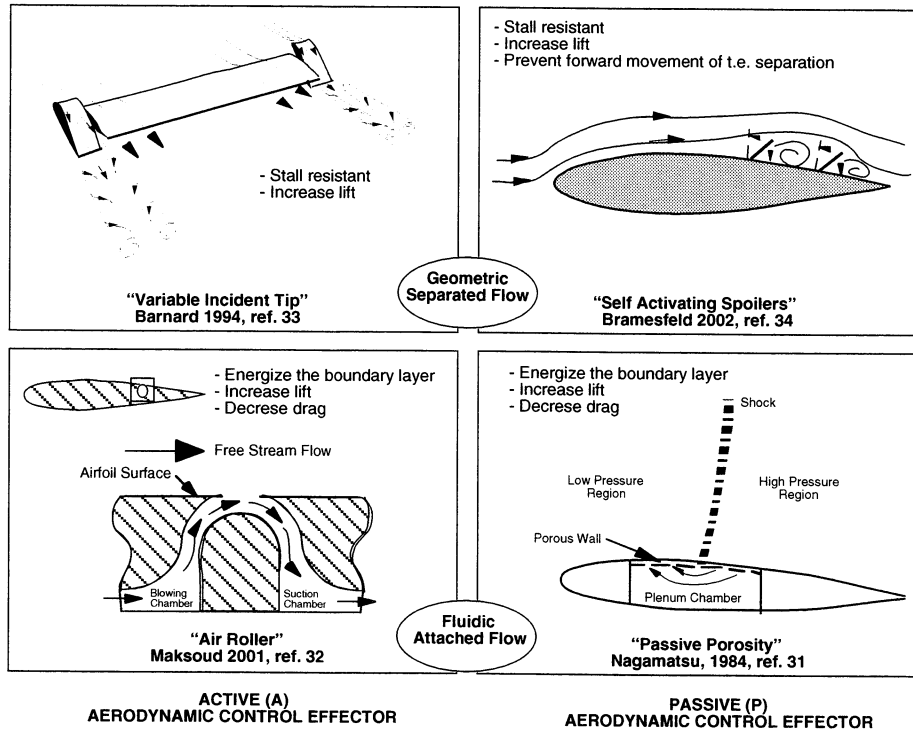


Figure 6. Examples of active and passive aerodynamic control effectors.

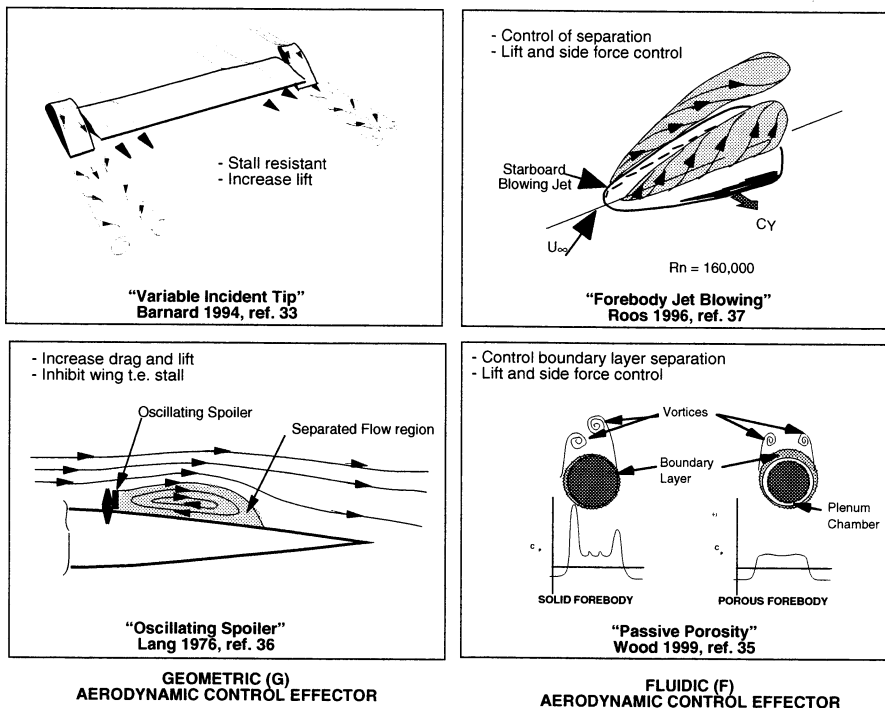


Figure 7. Examples of geometric and fluidic aerodynamic control effectors.

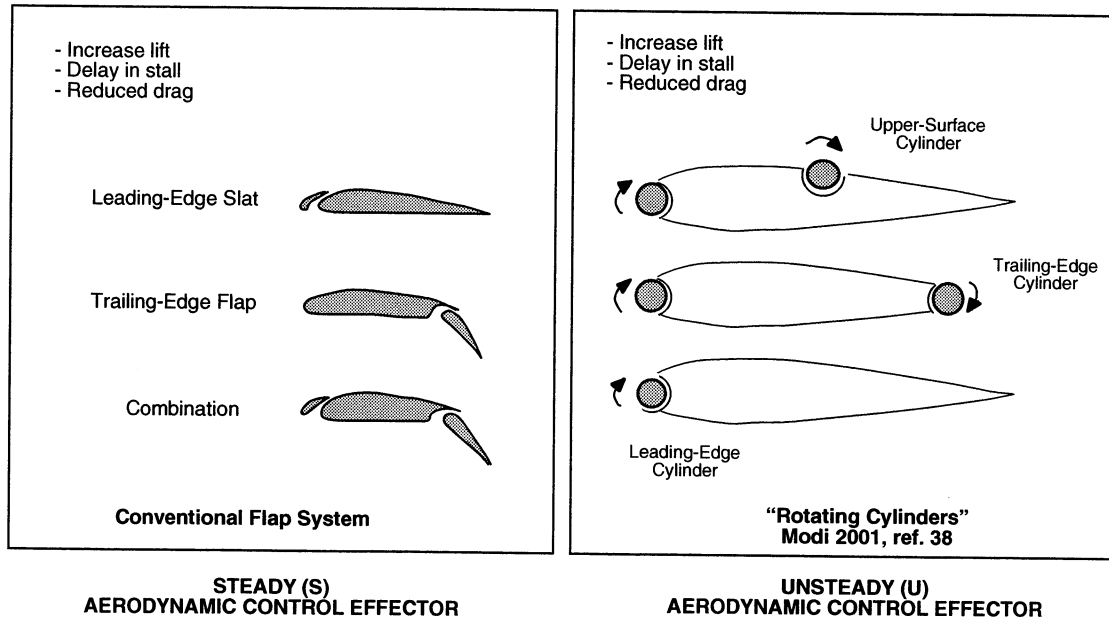


Figure 8. Examples of steady and unsteady aerodynamic control effectors.

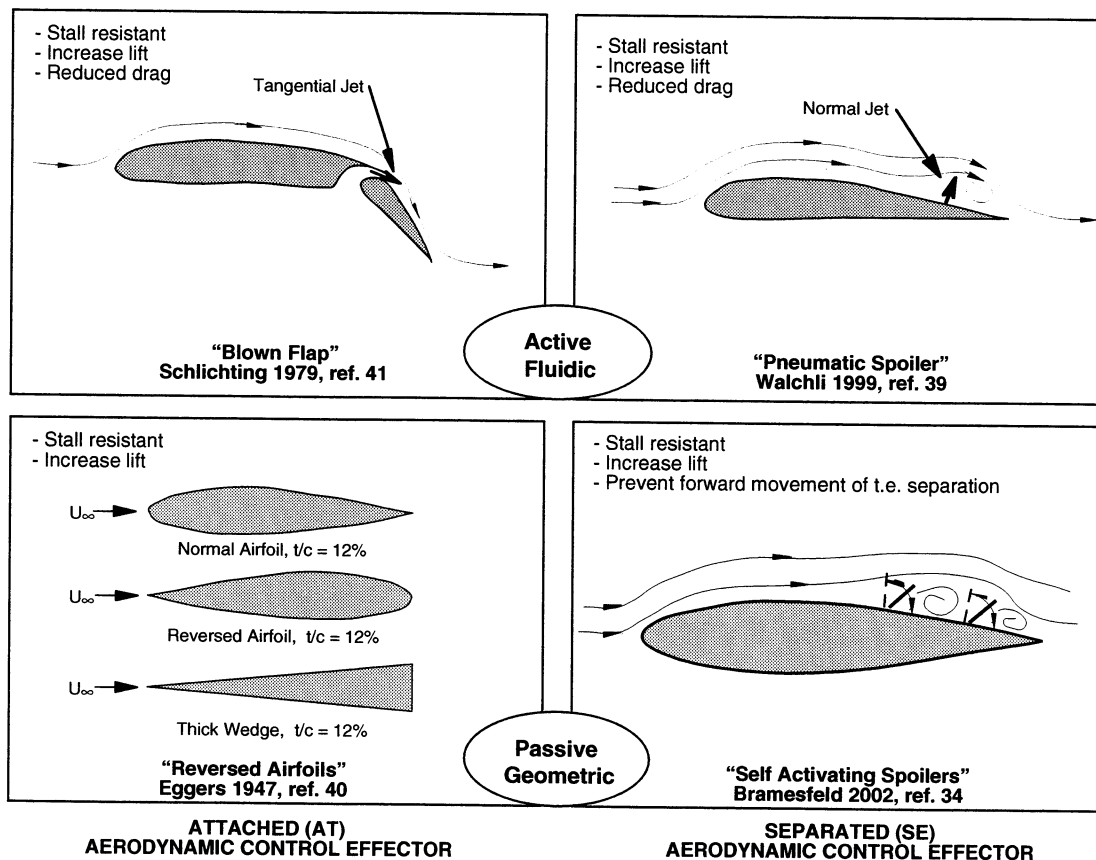


Figure 9. Examples of attached flow and separated flow aerodynamic control effectors.

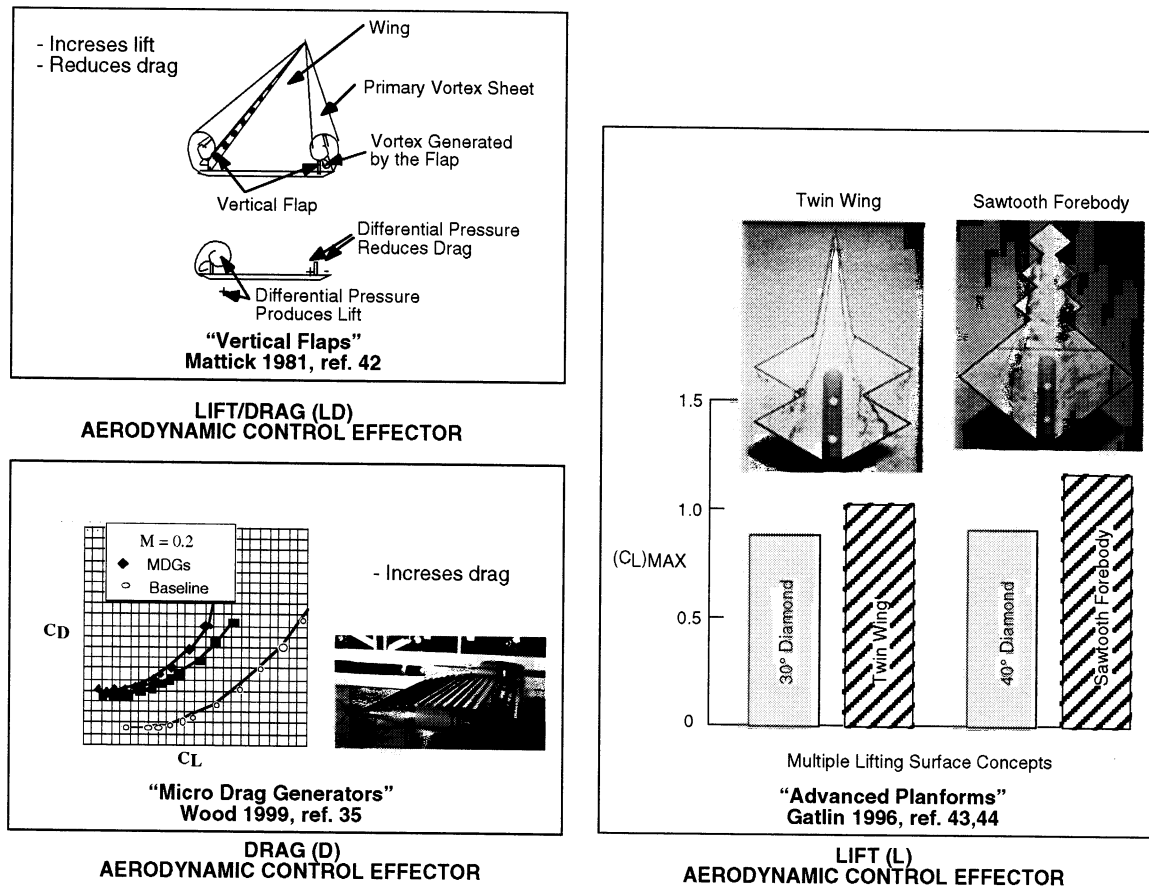


Figure 10 Examples of drag, lift, and lift/drag aerodynamic control effectors.

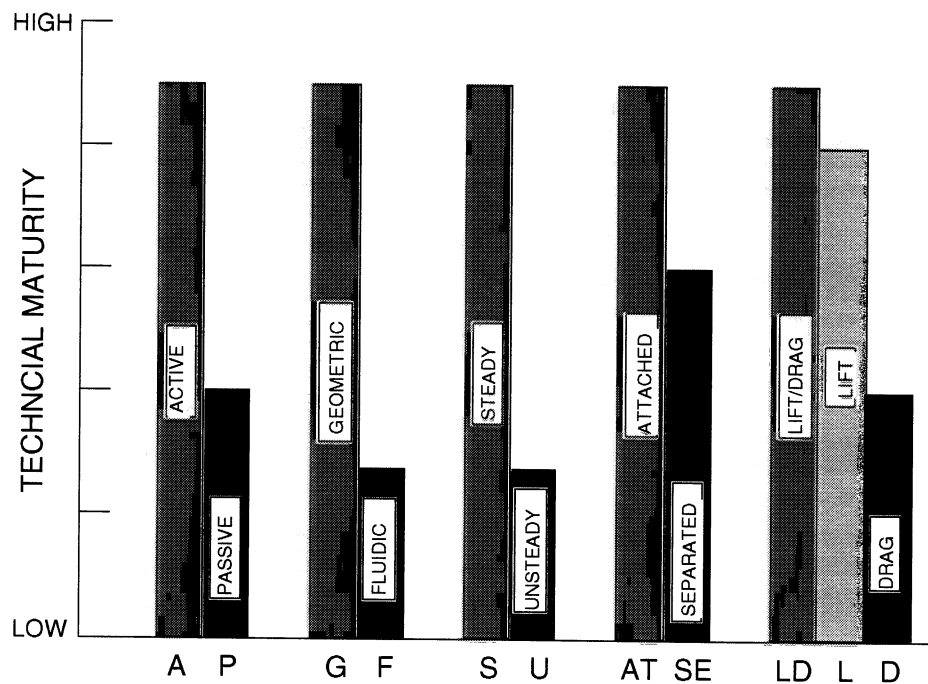


Figure 11. Technical maturity of aerodynamic control effector concepts.

UAV CLASS	AERODYNAMIC CONTROL EFFECTOR TYPES											COMMENTS
	A	P	G	F	S	U	AT	SE	L	D	LD	
MICRO	●	●	●	●	●	●	●	●	●	●	●	- Low energy environment - Low Rn - Low aerodynamic potential
MESO	●	●	●	●	●	●	●	●	●	●	●	- Low energy environment - Moderate aerodynamic potential
MACRO	●	●	●	●	●	●	●	●	●	●	●	- High energy environment - High Rn - High aerodynamic potential
MEGA	●	●	●	●	●	●	●	●	●	●	●	- Low - high energy environment - High Rn - High aerodynamic potential

Figure 12. Correlation of aerodynamic control effector type to UAV class..

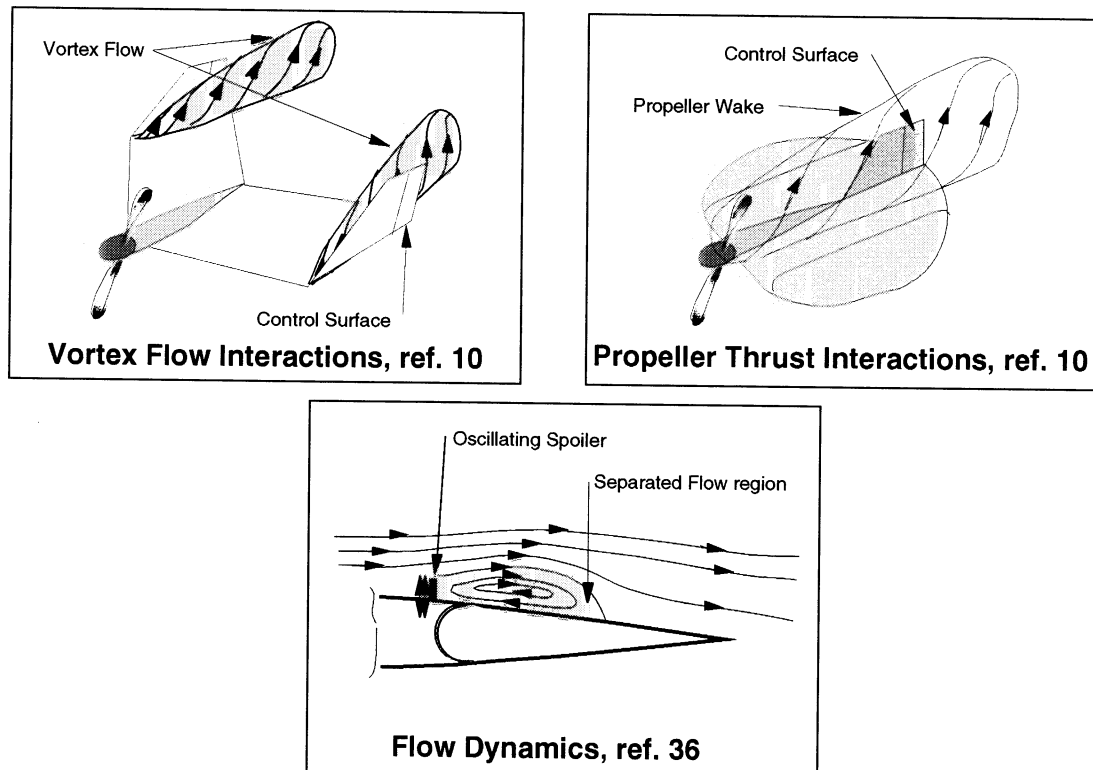














Figure 13. Concepts to augment the aerodynamic performance of aerodynamic control effector concepts.

UAV CLASS	ACE AERODYNAMIC POTENTIAL	AERODYNAMIC AUGMENTATION OF ACEs		
		THRUST	VORTEX FLOW	DYNAMICS
MICRO	LOW			
MESO	MODERATE			
MACRO	HIGH			
MEGA	HIGH			



 YES  
 NO

Figure 14. Assessment of the application ACE aerodynamic augmentation concepts to UAVs.

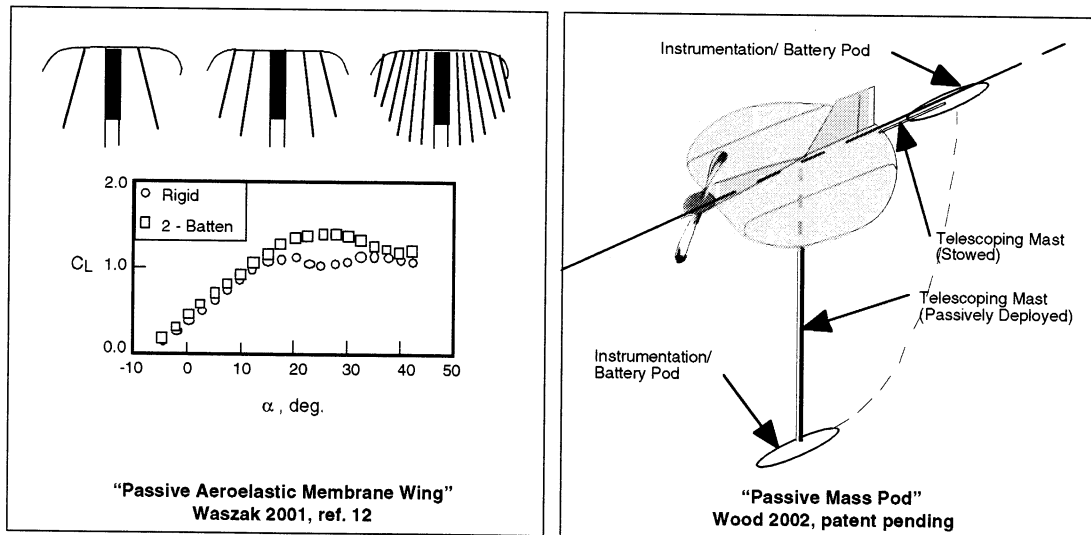


Figure 15. Stability augmentation concepts for UAVs...



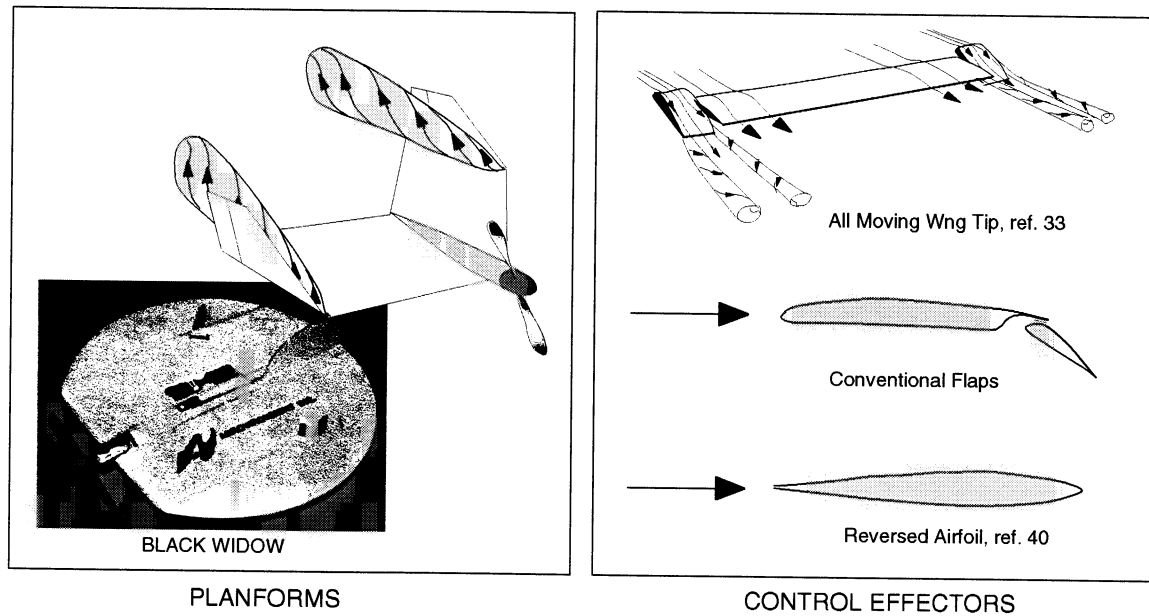


Figure 16. Candidate aerodynamic control effector concepts for Micro UAVs.

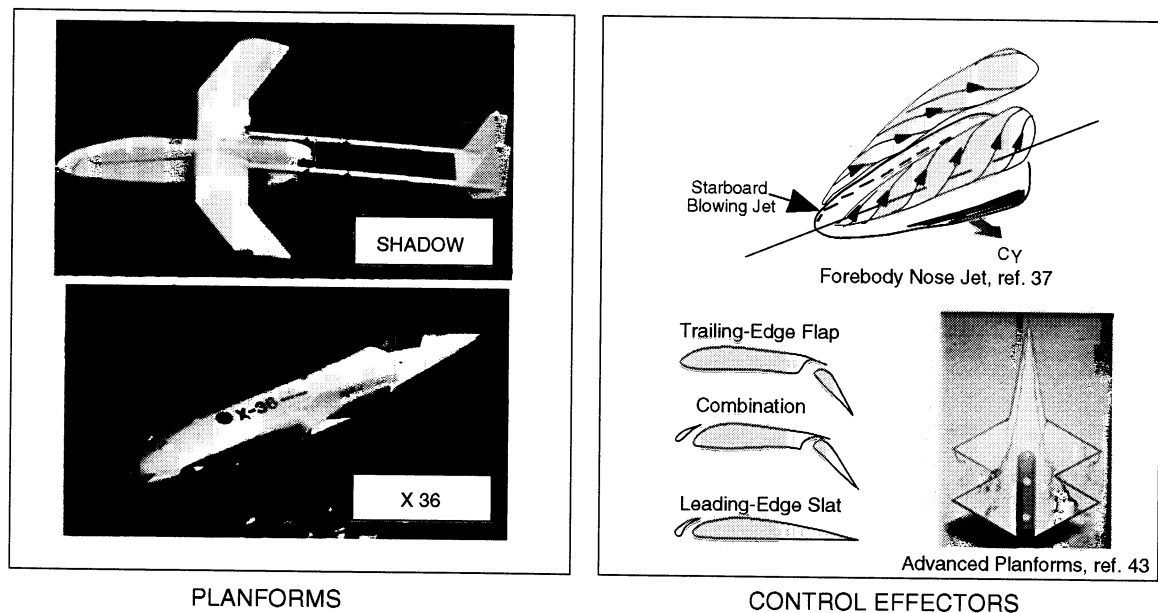


Figure 17. Candidate aerodynamic control effector concepts for Meso UAVs.

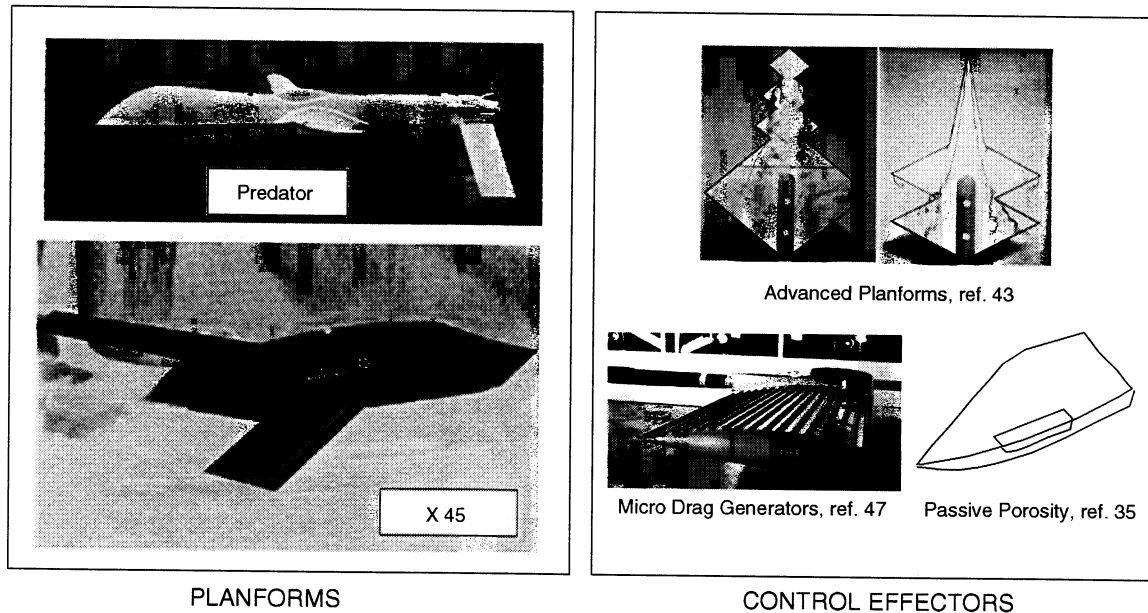


Figure 18. Candidate aerodynamic control effector concepts for Macro UAVs.

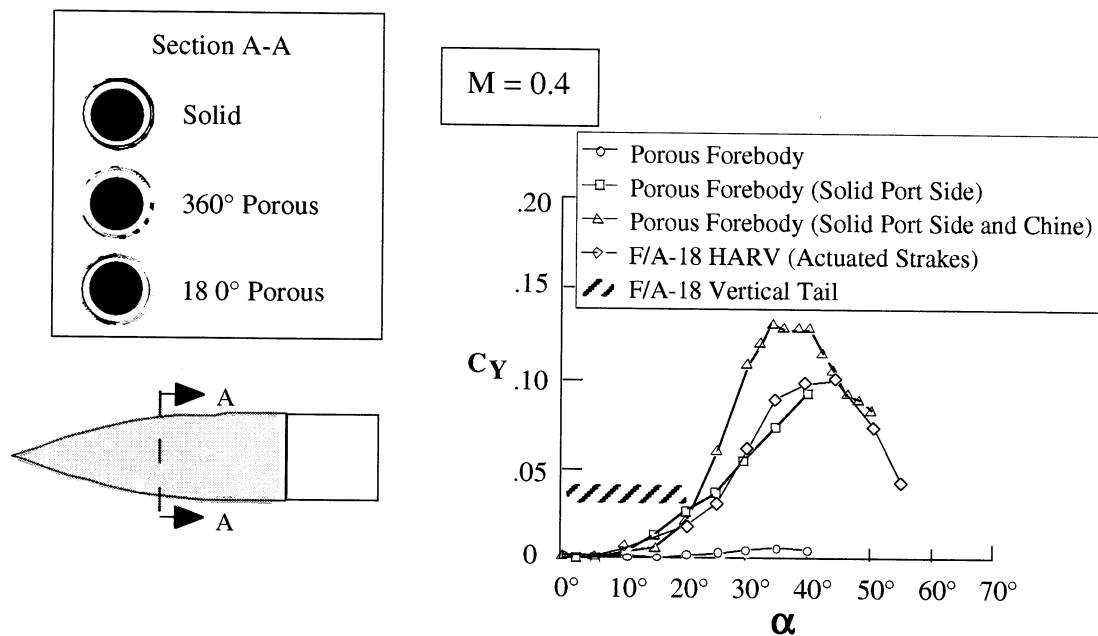


Figure 19. Plot of side force coefficient with angle of attack for various circumferential extents of passive porosity on a 5 caliber tangent-ogive. Ref.35.

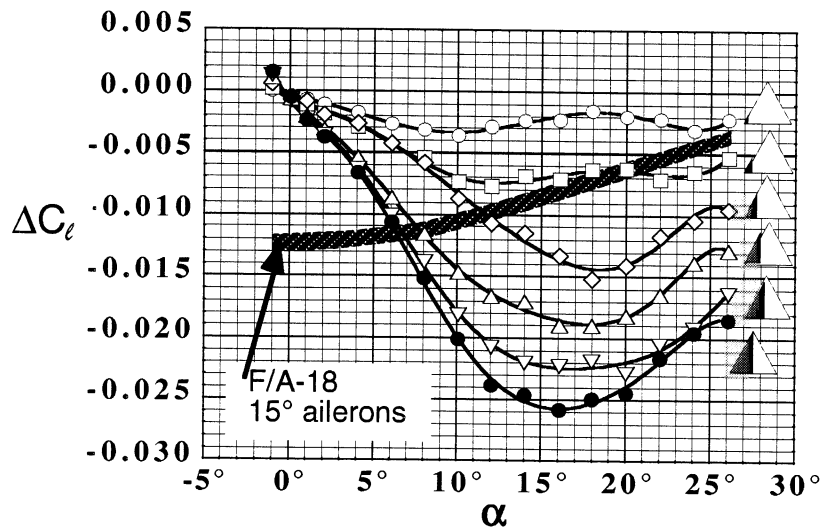


Figure 20. Plot of the increment in rolling moment coefficient with angle of attack for various spanwise extent of passive porosity on a 55° swept delta wing. Ref. 35.

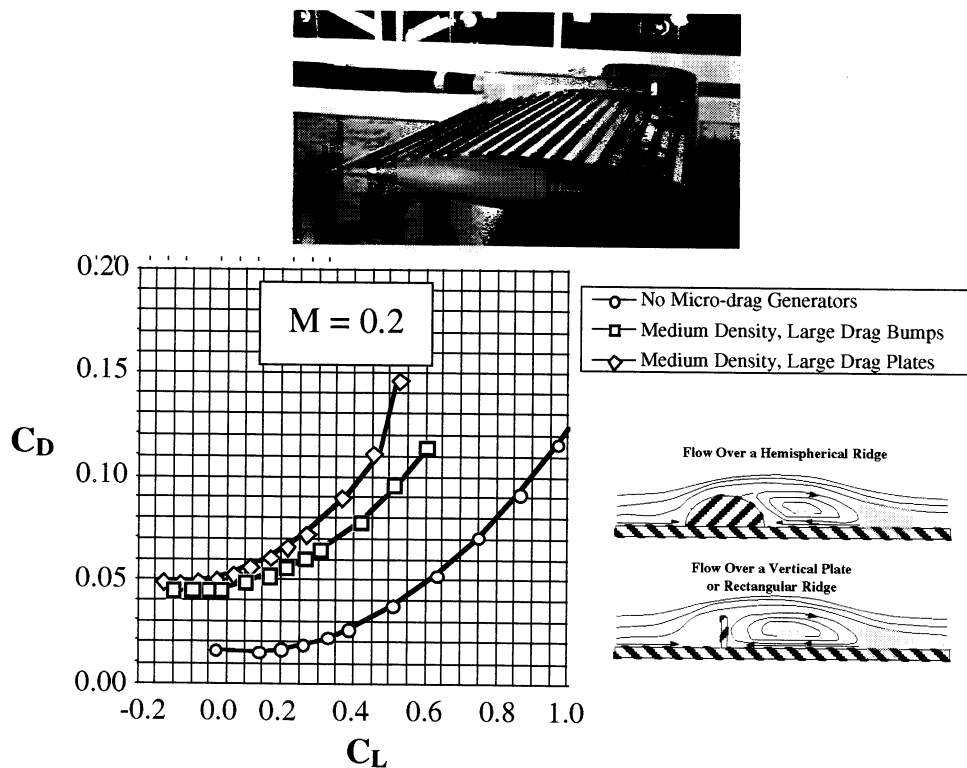


Figure 21. Aerodynamic performance and graphical details for micro drag generators applied to a high aspect ratio wing. Ref. 35.

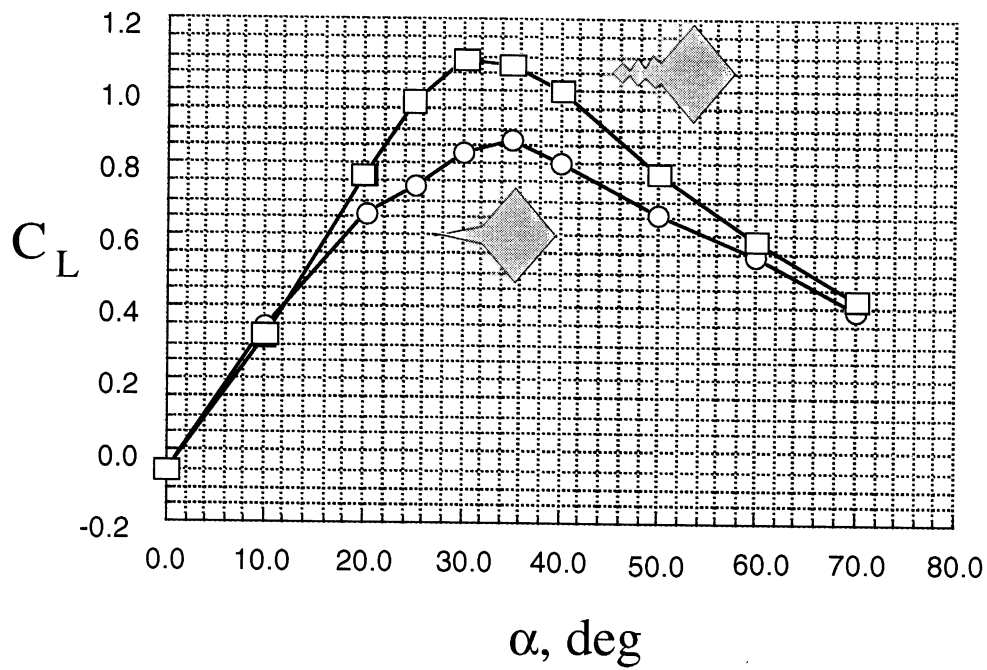


Figure 22. Plot of lift coefficient with angle of attack for a 40° diamond wing with and without 40° sawtooth forebody. Ref. 35

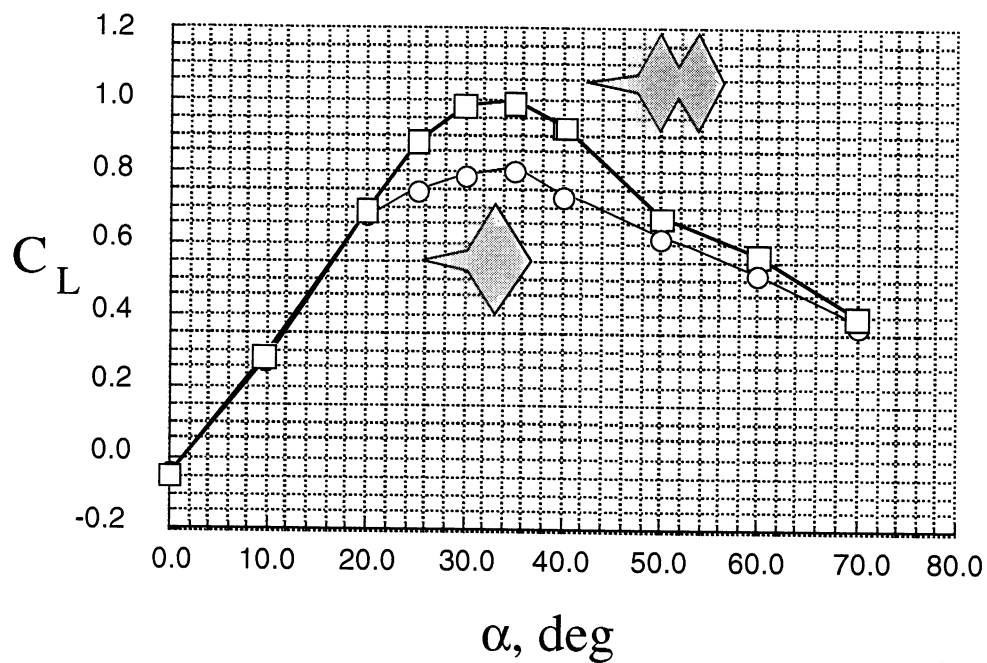


Figure 23 Plot of lift coefficient with angle of attack for a 30° diamond wing and 30° double diamond wing. Ref. 35.

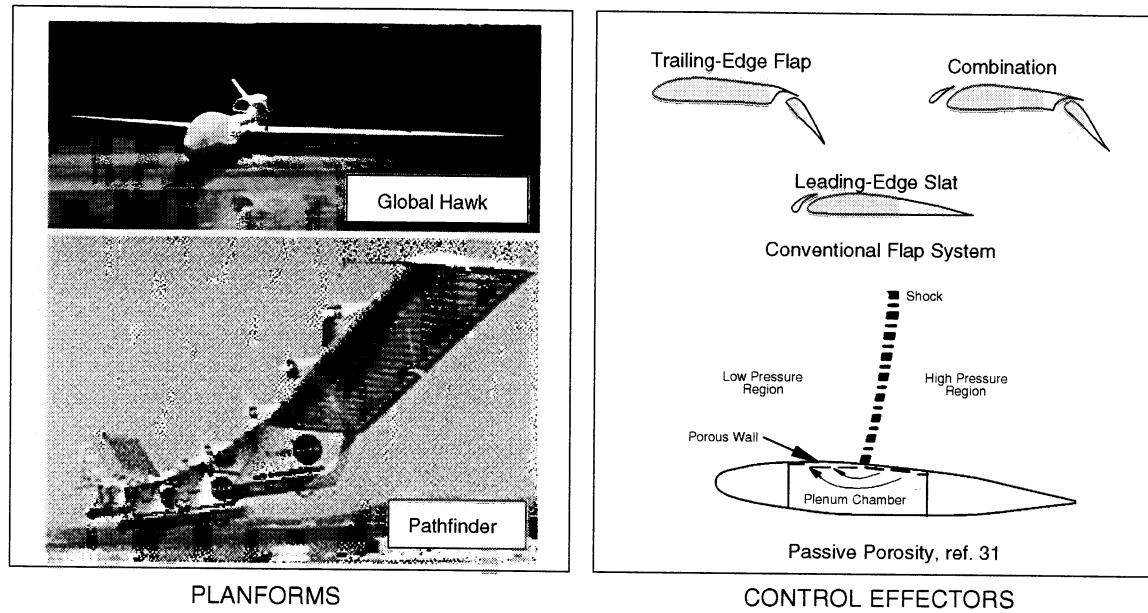


Figure 24. Candidate aerodynamic control effector concepts for Maega UAVs..

