Active Flow Control Using MEMS

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SUMMARY

This lecture presents an overview of the potential for the application of MEMS for the active control of fluid flows. In addition to providing a general overview of the underlying fluid mechanics and status of current research the relevance of this technology application to future military vehicle technologies is highlighted. The lecture identifies the potential benefits of the use of MEMS for controlling flow separation and reducing drag on a range of air vehicles and their propulsion systems. Because of the overview nature of this lecture the material presented has been extracted from a wide range of public domain sources both in the USA and Europe. Where, possible such material has been attributed to its originator. Apologies are made in circumstances where attributions have not been made.

1.0 INTRODUCTION

The performance, observability and affordability of most military vehicles are influenced by fluid physics either directly by their interaction with the surrounding air/water or indirectly through the many fluidic based systems they incorporate. The ability to manipulate a fluid flow to improve efficiency or performance is of immense technological importance and is currently one of the most high profile topics in fluid dynamics. The potential benefits of flow control include improved performance and manoeuvrability, affordability, increased range and payload, and environmental compliance. The intent of flow control may be to delay/advance transition, to suppress/enhance turbulence, or to prevent/promote separation. The resulting benefits include drag reduction, lift enhancement, mixing augmentation, heat transfer enhancement, and the suppression of flow-induced noise.

The desire to minimise drag (both skin friction and pressure) and to control flow separation in order to improve the high lift and propulsive performance of a wide range of vehicles is providing a driver for increased research activity in this field. In most cases drag and flow separation is dominated by the thin layer of fluid (often just a few millimetres thick), known as the boundary layer, that forms at the interface between the vehicle's components and the surrounding fluid. Over the last 20 years or so our knowledge about the evolution and propagation of boundary layers has increased significantly. This has been made possible through the advent of new experimental techniques and the development and use of computation tools such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). Developments of new manufacturing technologies such as Microfabricated Electro-Mechanical Systems (MEMS) and solid state actuator technologies such as piezo-electric materials and shape-memory alloys has also led to the possibility for active flow control to be realised at both a macro and micro scale.

MEMS technology offers the potential for the large-scale active control of coherent flow structures within the boundary layer. This could lead to the reduction of skin friction drag or the postponement of flow separation through the use of 'smart skins' capable of detecting and reacting to the state of the local boundary layer.

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Despite over a century of intensive research, turbulence remains largely an enigma that is analytically unapproachable yet practically very important. The mysteries of turbulence are only now being solved by the use of physical and numerical experiments, which is a far-from-trivial task at the high Reynolds numbers of practical interest to the aerospace engineer. Controlling a practical turbulent flow to achieve a desired effect such as drag reduction, lift enhancement or noise reduction is a very difficult task. Passive control methods, while always preferable, are generally limited in their utility. Brute force suppression, or taming, of turbulence via active, energy consuming control devices is always possible, but the penalty for doing so often exceeds any potential savings. The challenge is to actively achieve a desired effect with a minimum of energy expenditure by utilising the natural instabilities within the fluid structures to amplify control inputs.

2.0 THE NATURE OF TURBULENCE

Shear flow turbulence is dominated by a quasi-periodic sequence of large-scale structures often referred to as *turbulent coherent structures.* Coherent structures are not only quasi-periodic, but are different in size and shape depending on the location of these structures within the flow. Furthermore, the coherent structures are born, grow and die within the boundary layer, evolving in both space and time. The precise dynamics involved in the turbulence activities are far from clear. Qualitatively, according to the generally accepted school of thought, the process starts with pairs of elongated, counter rotating, stream-wise vortices buried within the near-wall sub-layer region. These vortices are often referred to as 'hairpin' vortices and arise in the first instance during the latter, non-linear stages of transition from laminar to turbulent flow. These hairpin vortices exist within a strong shear layer and induce low and high-speed regions between them. The low speed regions, close to the wall, termed *streaks*, grow downstream and develop inflectional velocity profiles. At the same time, the interface between the low and high-speed fluid begins to oscillate, signalling the onset of a secondary instability. The low speed region lifts up away from the wall as the oscillation amplitude increases and the flow rapidly breaks down (*bursts*) into a completely chaotic motion. In the sequence of turbulent activities within the boundary layer, there are two important events for energy production, called *sweeps* (or inrushes) and ejections (*bursts*). Over 80% of the turbulent kinetic energy production occurs during these events. The process described above is self- regenerating resulting in the continuous cyclic propagation of near near-wall hairpin vortices, streaks and bursts. There is still much speculation concerning the relationship between the stream-wise vortices and the streaks and significant further research in this field is required.

Large peaks in turbulent wall-shear stress are produced between a pair of counter-rotating longitudinal vortices as the high momentum fluid is brought down towards the wall during the near-wall burst events. These shear stress peaks give rise to the large increases in skin friction drag associated with a turbulent boundary layer compared to one that is laminar (typically an order of magnitude greater). Most of the activity in turbulent drag-reduction and separation control, both passive and active, relies on the manipulation by suppression, enhancement or modification of coherent turbulence structures.

3.0 ACTIVE FLOW CONTROL USING MEMS

At the present time MEMS and turbulence control are seen as the "Holy Grail" of fluid mechanics. One potential application for MEMS technology is the control of fluid flows through the active manipulation of the coherent structures that develop in a boundary layer.

Various methods of flow control have been implemented in practical engineering situations using conventional technologies (suction, tangential blowing, riblets, and vortex generators). However, all of the technologies applied can be considered as either passive or at most open-loop control by the addition of energy. Not all of these technologies are entirely effective at the efficient control of either free-shear layer or turbulent wall bounded flows. There have also been severe limitations as to the efficiency of conventional flow control technologies. For example, in attempting to reduce skin friction drag by suction (hybrid laminar flow) the penalties (weight, energy expenditure, and cost) associated with the control technology often exceed the benefits derived from its use. A way is needed to reduce the penalties and increase the benefits in order to achieve a more efficient control strategy.

Flow control is most efficient when applied at a region of the flow where susceptibility is high. i.e. in the critical regimes of the flow where flow instabilities magnify rapidly. The regions of boundary layer transition and flow separation are such areas. Therefore the delay/advancement of laminar to turbulent transition and the prevention/suppression of flow separation are relatively easy tasks to achieve. The reduction of skin friction in a stable, non-separating turbulent boundary layer is a much more difficult task. New ideas for turbulent flow control are based on the manipulation of the coherent structures that develop close to the wall. On practical engineering products such as the wings of aircraft and in the nacelles and components of their engines these flow structures occur at scales of tens to hundreds of microns. Technologies such as riblets can affect the near-wall turbulence generation process to achieve skin friction drag reductions of the order of 8 to 12%. However, newer ideas for turbulent flow control employing active MEMS scale technologies, giving potential reductions in skin friction drag of 50% or more have been spurred on by recent developments in the understanding of boundary layer physics, chaos control and fabrication technologies. Futuristic concepts are envisioned where large arrays of inexpensive, intelligent, interactive flow sensors and actuators are built into aerodynamic surfaces to interact with the organised flow structures that occur randomly in the boundary layer to achieve efficient control of the flow.

Research into the application of MEMS for flow control has been ongoing in the USA for a number of years. Significant activity exists at a number of US universities where financial support from the Government via the AFOSR and DARPA among others, is being directed. Recent experiments and simulations in the USA have demonstrated the fundamental feasibility of active boundary layer control. Europe is also involved in a number of activities to study the potential of MEMS for active flow control. These activities involve both academic and industrial organisations. Most European research activities revolve around the promotion or delay of flow separation since this is perceived as being realisable within a much nearer timeframe than turbulent drag reduction. In addition to the issues of the fabrication and application of sensor and actuator technologies studies are also ongoing to develop optimum control strategies and to develop design and analysis tools.

4.0 CONCLUDING REMARKS

Although there are important activities going on to investigate the application of new technologies such as MEMS for active flow control it is unlikely that any will be mature for application, other than as a component of very simple systems, within the next decade or two.

Whether or not any of the flow control technologies will see a widespread application on a production aircraft in the future depends on two important factors:

- Does it work?
- Does it make practical economic sense?

The first question is probably the easiest criteria to address. In the first instance any new technology has to be demonstrated experimentally at large scale under relevant Reynolds and Mach numbers. It must then be proven to operate in the presence of real world conditions and shown to enhance or improve a valuable performance metric. Any system must be demonstrated to be manufacturable, robust, reliable, maintainable and inspectable. Any performance side effects must be acceptable.

The second criterion is more difficult to assess and the answer may change with evolving worldwide economic market and political conditions. To be viable any flow control application must have a favourable overall cost/benefit. The initial design/integration cost combined with the cost of energy expenditure during operation must be outweighed by any benefits obtained. Issues related to the legal/regulatory standpoints of product liability, safety, and environmental/acoustic pollution also need to be resolved.

Although many flow control technologies have been identified and researched at the basic level for many decades few have ever reached maturity and full-scale deployment on a commercial product. It could be argued that the basic research community is not sufficiently aware of the practical issues of implementation and that in some cases non-application useful research is carried out while in other areas the research is not carried far enough to allow technological evaluation. With the limited research investment available it is becoming essential that the research community work more closely with the application community to develop practical technologies in the most efficient manner. This requires all involved to work in a multidisciplinary environment to develop the basic tools and understanding and then to progress this towards large-scale demonstration and evaluation. It is important that unworkable concepts are filtered at the earliest possible opportunity in order to avoid unnecessary effort being directed at hopeless causes. Early in the assessment process it is essential that industrial studies be made to identify the potential benefits and practical implications of any new flow control technology. In order to do this industry requires robust, rapid tools with which to undertake aerodynamic analysis.

Turbulent flow control should not just be considered as a fix to solve a problem or a means of improving even further the performance of an already optimised design. Consideration should be given to employing turbulent flow control early in the design optimisation process. A commercially better design may be obtained by the use of flow control to recoup performance losses associated with simplifying other aspects of the design to reduce manufacturing costs, system complexity or structural weight (e.g., reduced sweep, thicker wings, smaller, simpler high lift systems).

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RTO

AVT Lecture Series 235

MEMS Aerospace Applications

Micro Flow Control (1)

Dr. Clyde Warsop

Lecture Outline

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- Introduction
  - What is it micro flow control about?
  - Why do we want to do it?
- Potential applications
- State-of-the-art
- Barriers to success

What is Micro Flow Control?

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- Manipulation of a fluid flow to effect a desired change leading to a practical benefit
  - Flow control is not new – it's what Aero/hydrodynamics has always been about
  - Reduce Drag
  - Delay/promote flow separation
  - Enhance mixing

Engineering Relevance

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- External interactions of all vehicles with external fluids (air, water)
- Flows associated with propulsion systems, turbomachinery and IC engines (intakes, fans,compressors, combustion, turbines, exhausts)
- Fluid systems (pneumatics, cooling, hydraulics)

Boundary Layer Development

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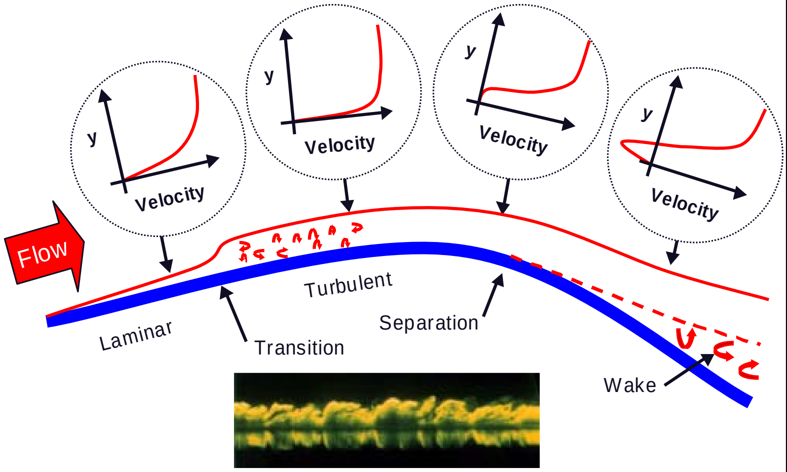

The Nature of Turbulence

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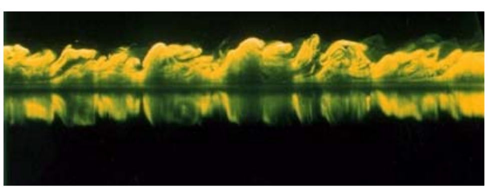
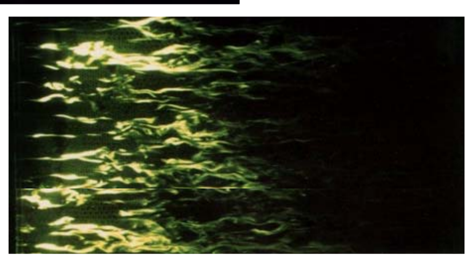
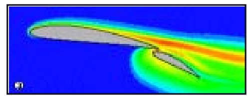


Side view

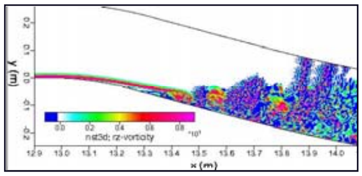


Plan view in near-wall region

Large-Scale Eddy Structures

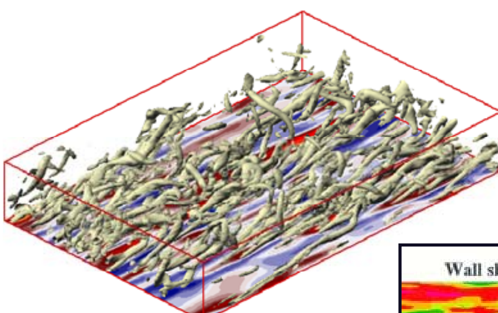


Application to high-lift trailing-edge separations

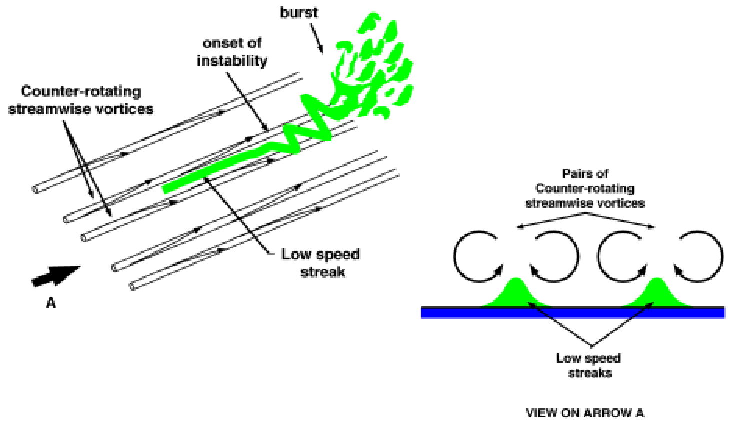


Excite interaction between large-scale span-wise eddy structures that occur close to point of separation.

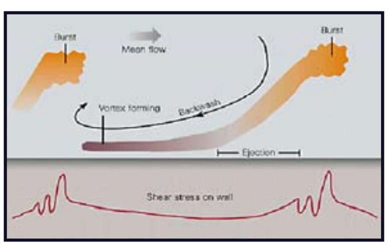
Near-Wall Coherent Structures

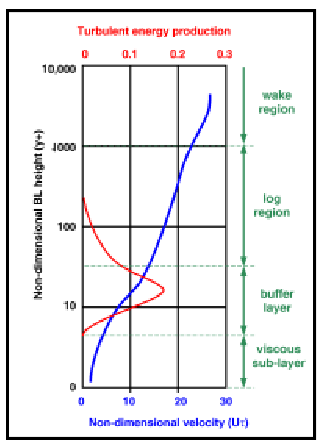


Near-Wall Coherent Structures



Turbulent Energy Production





Engineering Objectives

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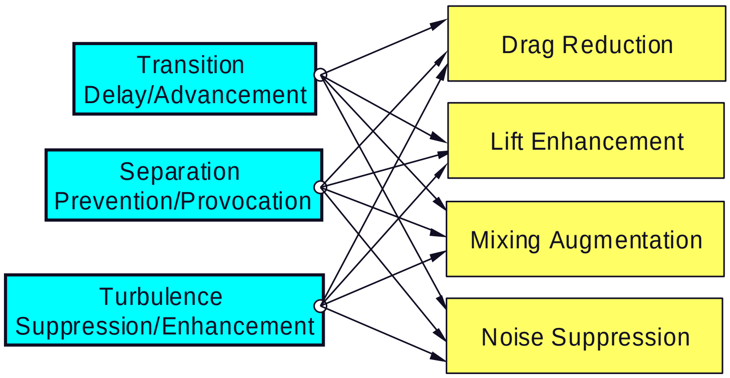

Relation Between Flow Control Objectives

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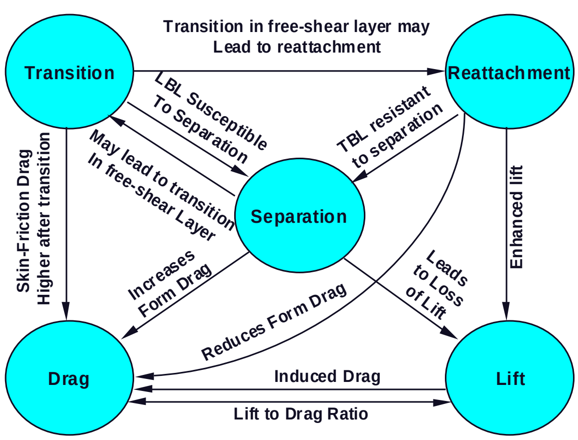
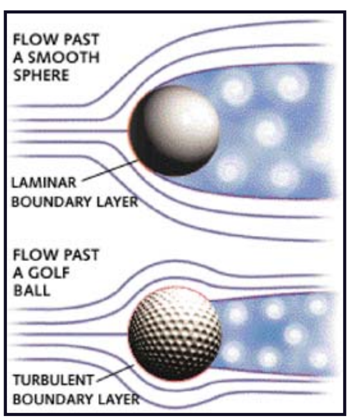


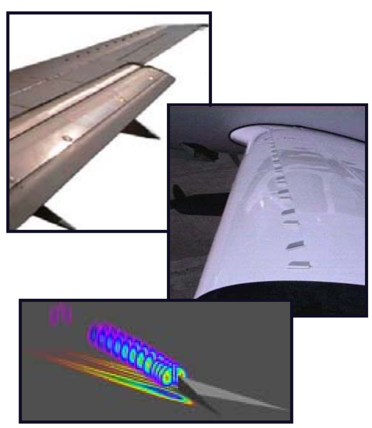
Classification of Control Strategies

- Flow control strategies
  - Passive
  - Active
    - Predetermined
    - Reactive
      - Feed-forward
      - Feed-back
        - Adaptive
        - Physical Model
        - Dynamical Systems
        - Optimal Control

Passive Separation Control



Dimples on a golf ball



Vortex Generators

Passive Drag Reduction

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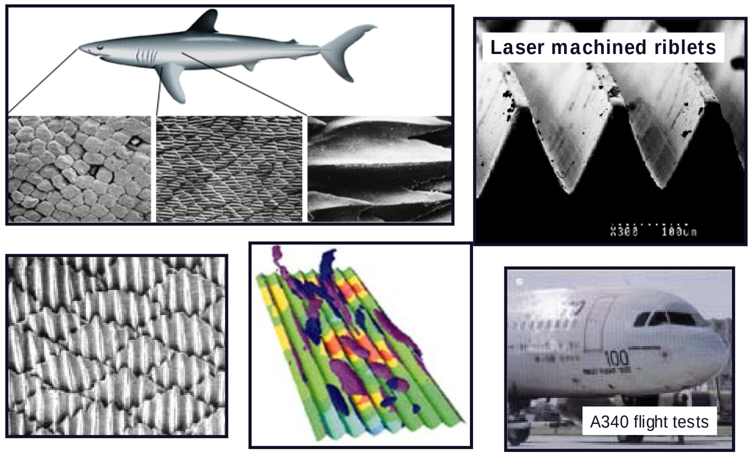

Characteristics of Classical Flow Control

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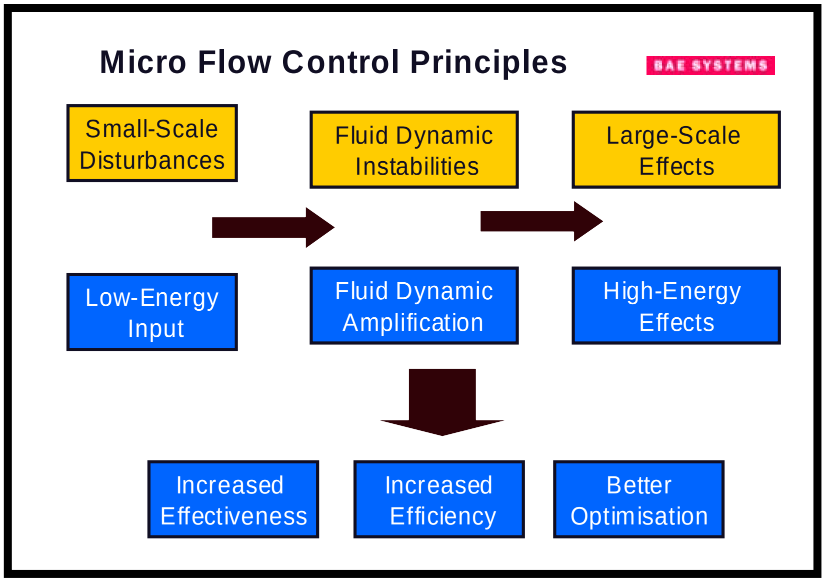
- Passive
  - Riblets, vortex generators
  - Always there - parasitic penalties
- Addition of energy
  - Steady blowing/suction
- Low technology
- Not necessarily fully optimised


Micro Flow Control Principles
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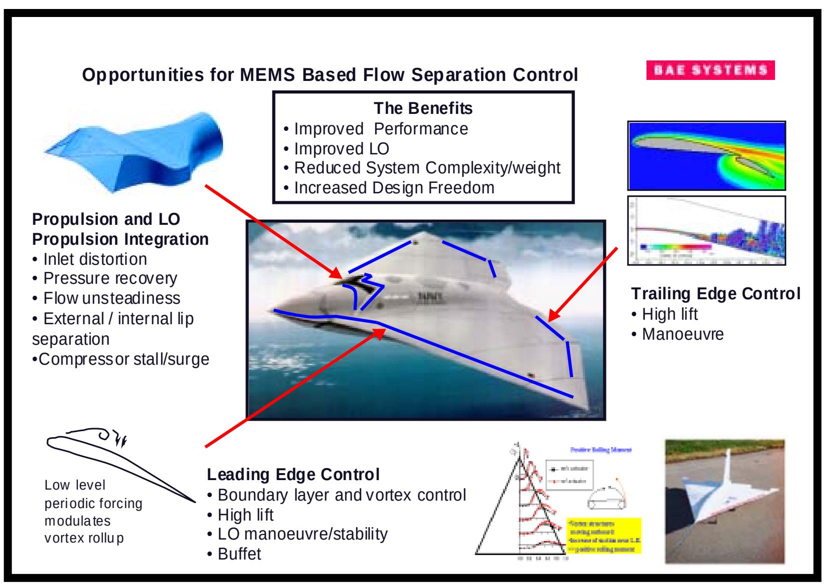
Small-Scale Disturbances
Fluid Dynamic Instabilities
Large-Scale Effects
Low-Energy Input
Fluid Dynamic Amplification
High-Energy Effects
Increased Effectiveness
Increased Efficiency
Better Optimisation


Opportunities for MEMS Based Flow Separation Control
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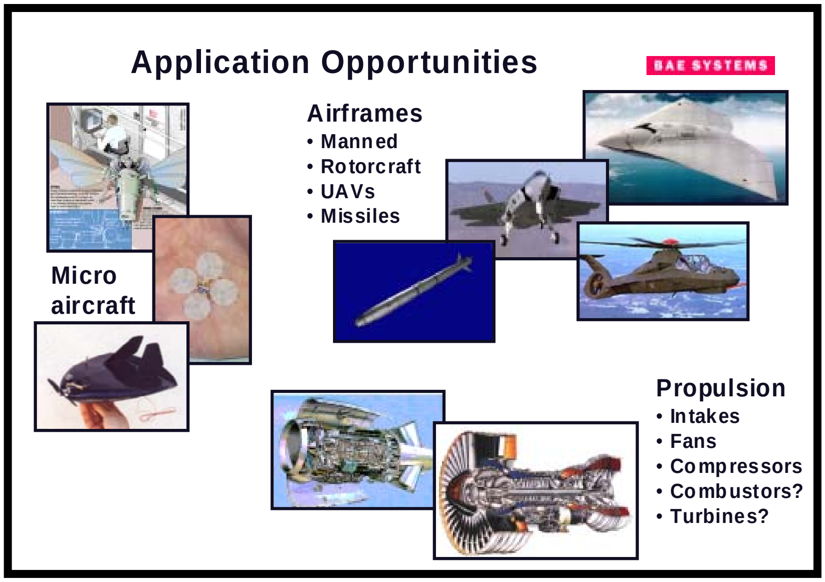
The Benefits
• Improved Performance
• Improved LO
• Reduced System Complexity/weight
• Increased Design Freedom
Propulsion and LO Propulsion Integration
• Inlet distortion
• Pressure recovery
• Flow unsteadiness
• External / internal lip separation
•Compressor stall/surge
Trailing Edge Control
• High lift
• Manoeuvre
Low level periodic forcing modulates vortex rollup
Leading Edge Control
• Boundary layer and vortex control
• High lift
• LO manoeuvre/stability
• Buffet


Application Opportunities
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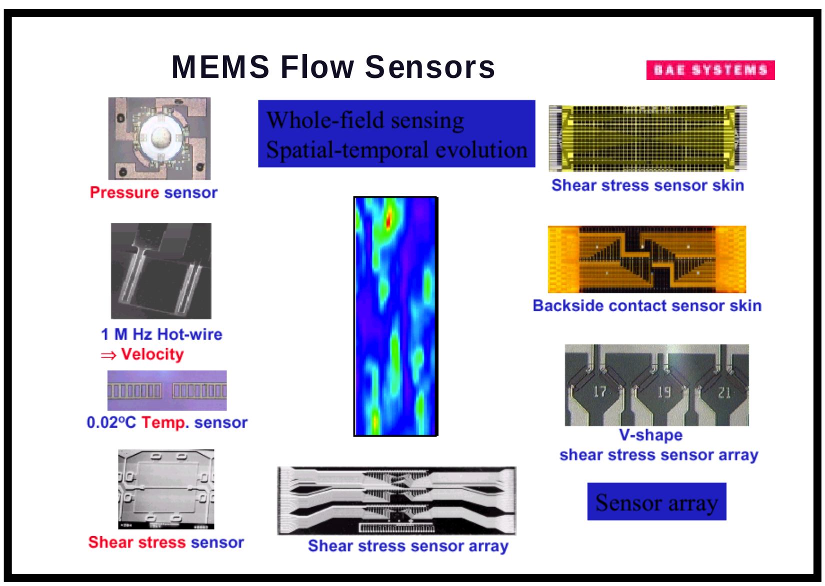
Micro aircraft
Airframes
• Manned
• Rotorcraft
• UAVs
• Missiles
Propulsion
• Intakes
• Fans
• Compressors
• Combustors?
• Turbines?


MEMS Flow Sensors
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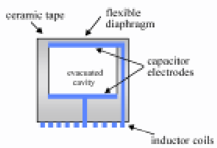
Pressure sensor
Whole-field sensing
Spatial-temporal evolution
Shear stress sensor skin
1 M Hz Hot-wire
⇒ Velocity
0.02°C Temp. sensor
Backside contact sensor skin
V-shape
shear stress sensor array
Sensor array
Shear stress sensor
Shear stress sensor array

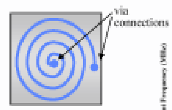
High Temperature Pressure Sensor

BAE SYSTEMS

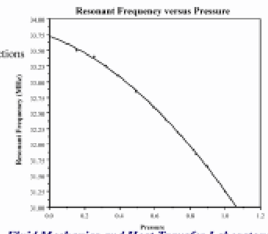
- A silicon diaphragm combined with a ceramic laminate approach and remote readout for sensing high temperatures in turbine engine compressors.
- As the pressure increases, the capacitance increases and the resonant frequency decreases.
- Resonant frequency is read out by determination of the impedance of an *external* loop antenna---no wiring and power supply is required.



side view



bottom view



$\omega = 1/\sqrt{LC} \quad C = \varepsilon A/d$

Georgia Institute of Technology | MiRC MEMS Laboratory | Fluid Mechanics and Heat Transfer Laboratory

Metal Surface Pressure Sensor

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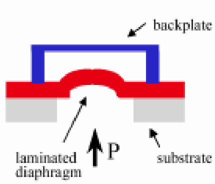
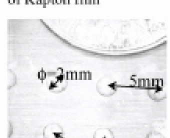
- A stainless steel/metal/organic laminate approach combined with surface micromachined electroplated structures for external aerodynamic applications
- Capacitive pressure sensor (monitor capacitance between diaphragm and surface micromachined backplate)
- Materials: *Substrate*: stainless steel (20 mil); *Pressure membrane*: Kapton polyimide film (2 mil); *Backplate*: electroplated nickel (approximately 15 µm thick)

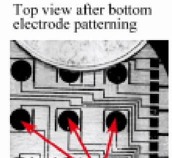


Top view after lamination of Kapton film



Milled pressure inlet holes viewed through Kapton film

Top view after bottom electrode patterning



Pressure-sensitive Kapton diaphragm covered by bottom electrodes

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Boeing/Endevco Pressure Belt

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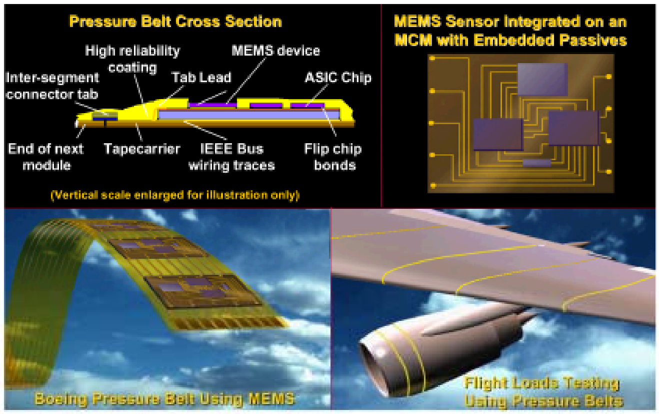

Boeing/Endevco Pressure Belt

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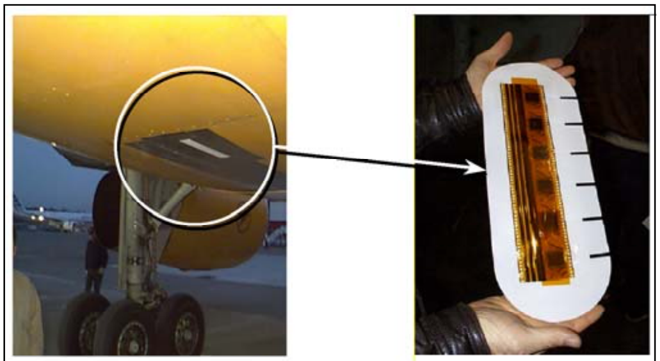

Boeing MEMS Pressure Belt on Belly Tank of 737

Floating Element Shear-Stress Sensor

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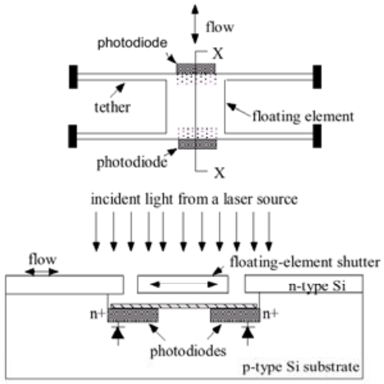

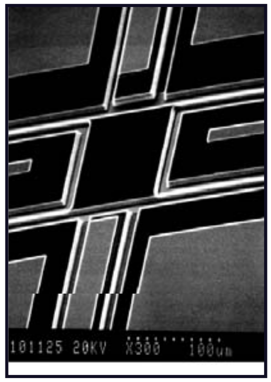

Schematic of the Optical Floating-Element Shear Stress sensor (Padmanabhan *et al.*).

Thermal Wall-Shear-Stress Sensors

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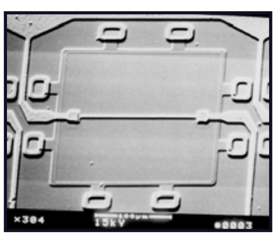
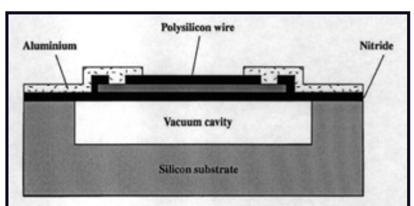
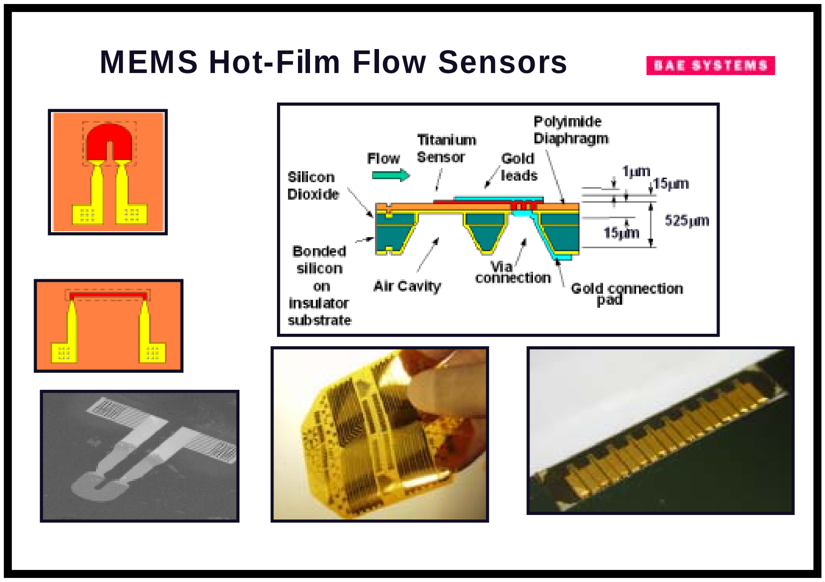
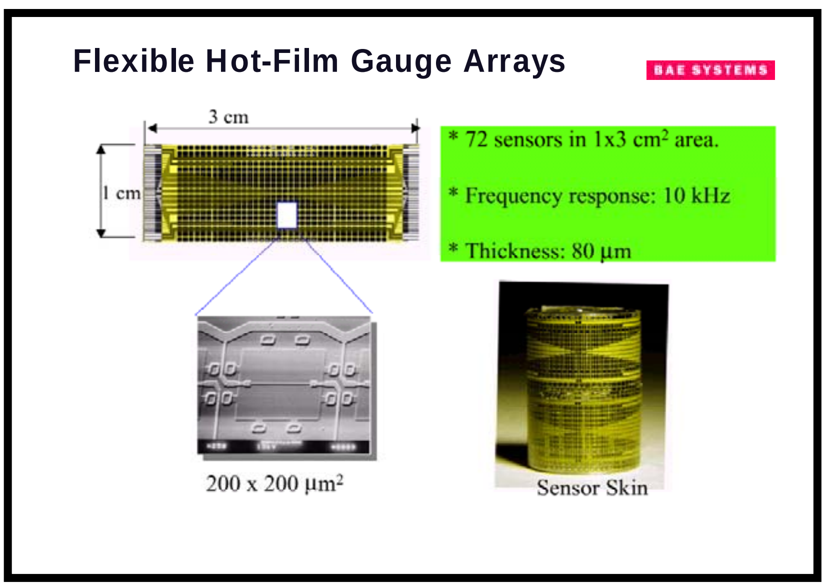




Cross-sectional structure of a single shear-stress sensor. From Jiang et al.

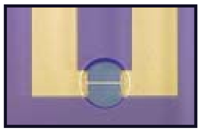
Sensing element 150 microns long, 10 microns wide


MEMS Hot-Film Flow Sensors
BAE SYSTEMS
Polyimide Diaphragm
Titanium Sensor
Flow
Gold leads
Silicon Dioxide
1µm
15µm
525µm
15µm
Bonded silicon on insulator substrate
Air Cavity
Via connection
Gold connection pad

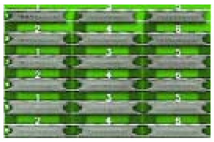

Flexible Hot-Film Gauge Arrays
BAE SYSTEMS
3 cm
1 cm
* 72 sensors in 1x3 cm² area.
* Frequency response: 10 kHz
* Thickness: 80 µm
200 x 200 µm²
Sensor Skin

MEMS Flow Actuators

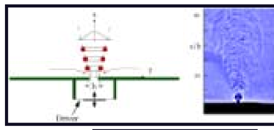
BAE SYSTEMS

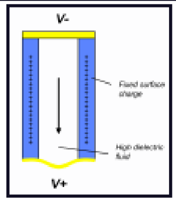


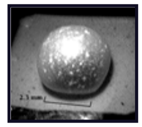
Thermal



Electro-hydrodynamic





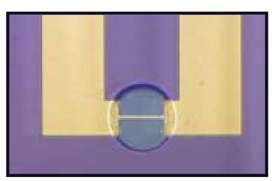


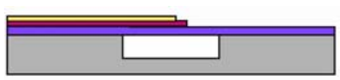
Momentum injection

Thermal Actuators

BAE SYSTEMS

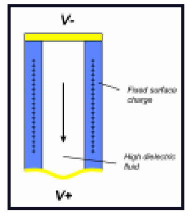
- Add heat to fluid
- Actuation effects:
  - Density change (gases)
  - Viscosity change (Opposite effects for gasses and liquids)
- Advantages
  - Extremely simple
  - No moving parts
- Disadvantages
  - Thermal loss to substrate
    - Inefficient
    - Lowers bandwidth

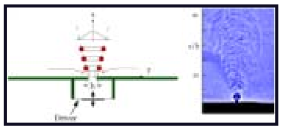


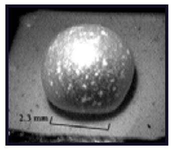


Momentum Injection Actuators

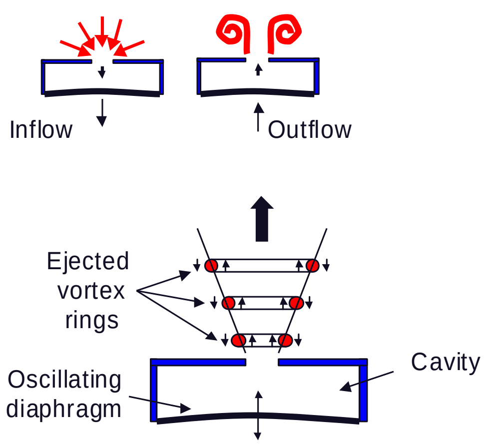
- More direct control authority
  - Surface displacement
  - Velocity
  - Vorticity
- Many varieties
  - Surface motion (normal/lateral)
  - Fluidic injection Blowing/ suction
  - Direct momentum injection (synthetic jets)

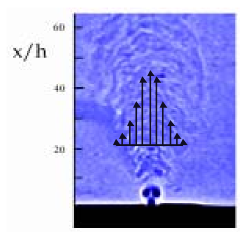


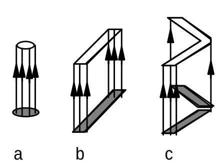


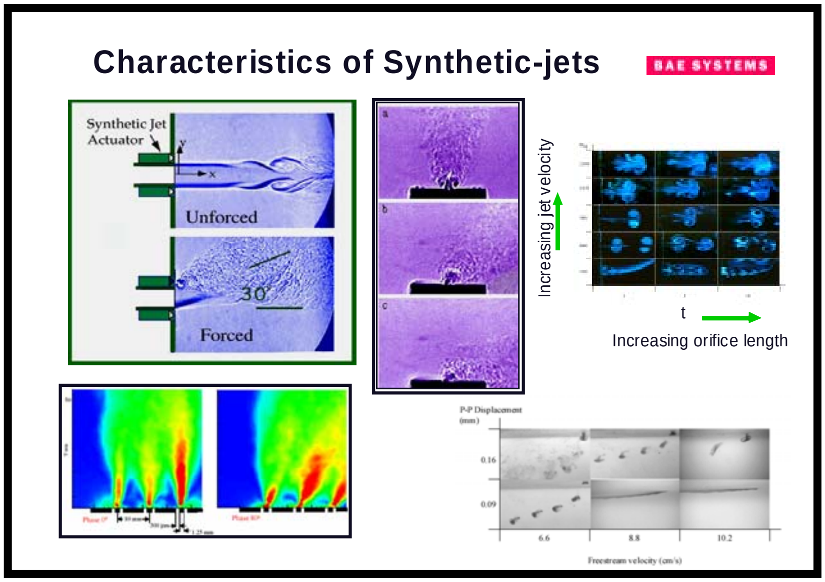


Synthetic-Jet Actuators








Characteristics of Synthetic-jets
BAE SYSTEMS
Synthetic Jet Actuator
y
x
Unforced
30°
Forced
a
b
c
Increasing jet velocity
t
Increasing orifice length
P-P Displacement (mm)
0.16
0.09
6.6
8.8
10.2
Freestream velocity (cm/s)

RTO

AVT Lecture Series 235

MEMS Aerospace Applications

Micro Flow Control (2)

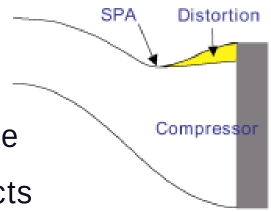
Dr. Clyde Warsop

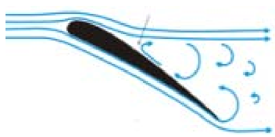
Lecture Outline

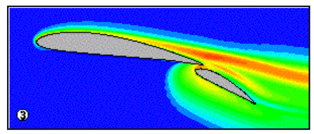
- Examples of Research
  - Flow Separation
  - Vehicle Manoeuvre
  - Airframe and Turbomachinery Applications
  - Micro Cooling
- Implementation Issues
- Conclusions and Outlook

Consequences of Flow Separation

- Limits maximum lift
- Increased pressure drag
- Unsteadiness ⇒ buffet/fatigue
- Flow distortions/losses in ducts
- limits compressor stall/surge margins







Benefits of Flow Separation Control

- Increased performance (higher, faster, further, more agile)
- Reduced cost (arise from reductions in weight & size, reduced mechanical system complexity, reduced maintenance costs, reduced fuel burn)
- Reduced size (directly related to weight and cost, also benefits reduced signature)
- Reduced weight (directly related to size & cost)
- Reduced maintenance costs (simpler, modularly maintainable MEMS systems could be cheaper than conventional high-lift and control devices)
- Reduced signatures (replace conventional stabilising and control surfaces (eg tail and fins) to reduced RCS, increased mixing of engine exhausts leading to reduced IR signatures)

Strategies

BAE SYSTEMS

r the wall

enhance mixing with

ructures to increase
ents

nt structures to
rsting events

erators (where BL is

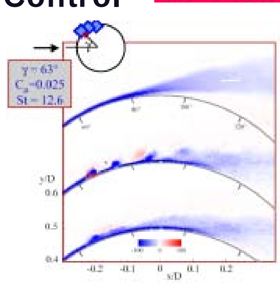
e eddy structures in the

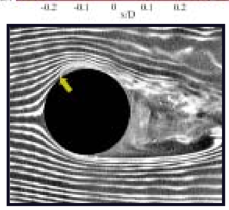
Condition BL before separation.

control BL at separation.

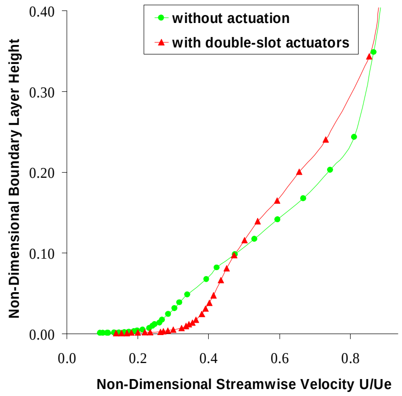
S n Control

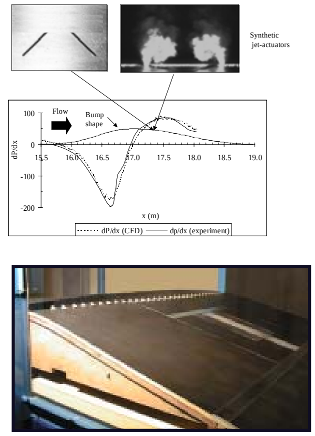
BAE SYSTEMS



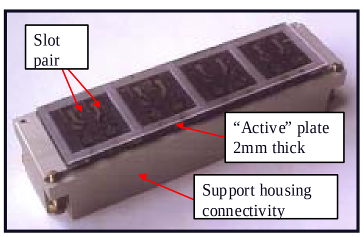


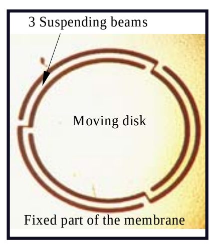
Synthetic/pulsed Jets for Separation Control

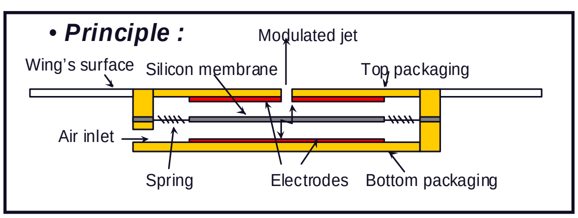




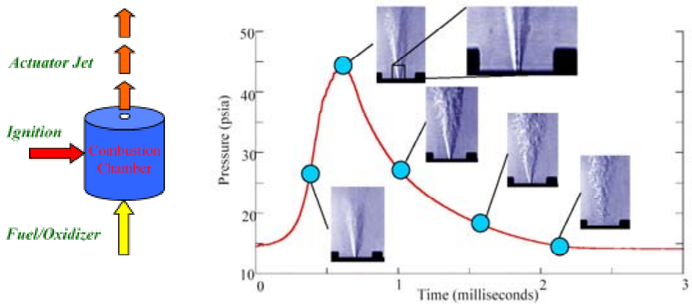
MEMS Pulsed-Jet Actuator



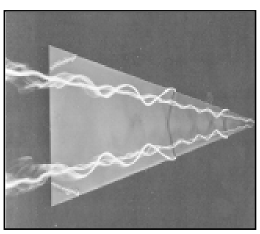




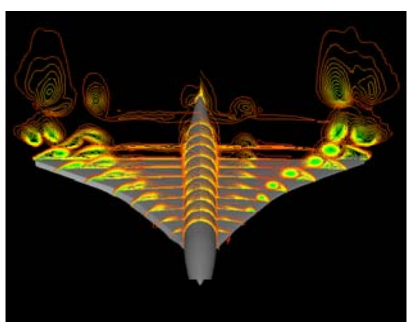
High Momentum Combustion Actuator (Georgia Tech)



Leading Edge Vortex Control (UCLA)

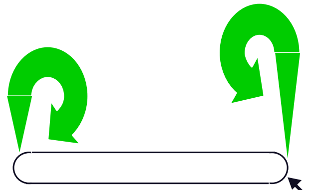


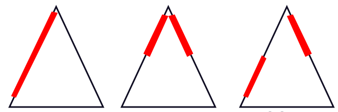
Leading edge vortices contribute up to 40% lift



Small changes to vortex strength/position → significant changes to loads and hence lift/control forces

Leading-Edge Vortex Control

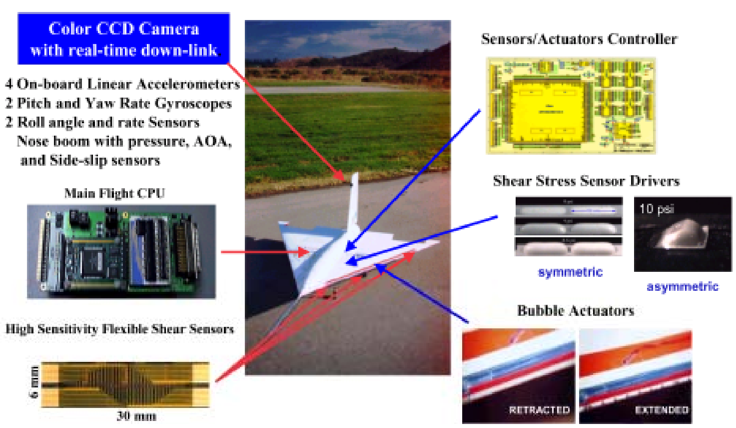


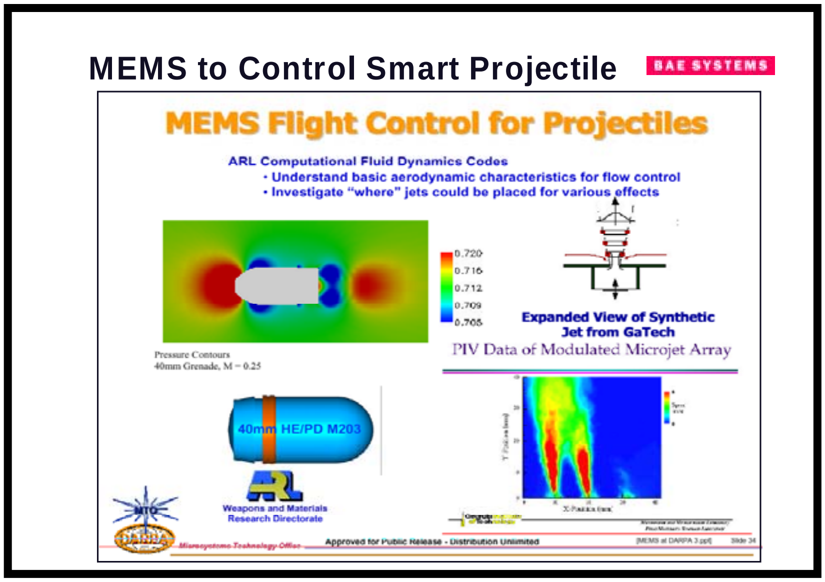


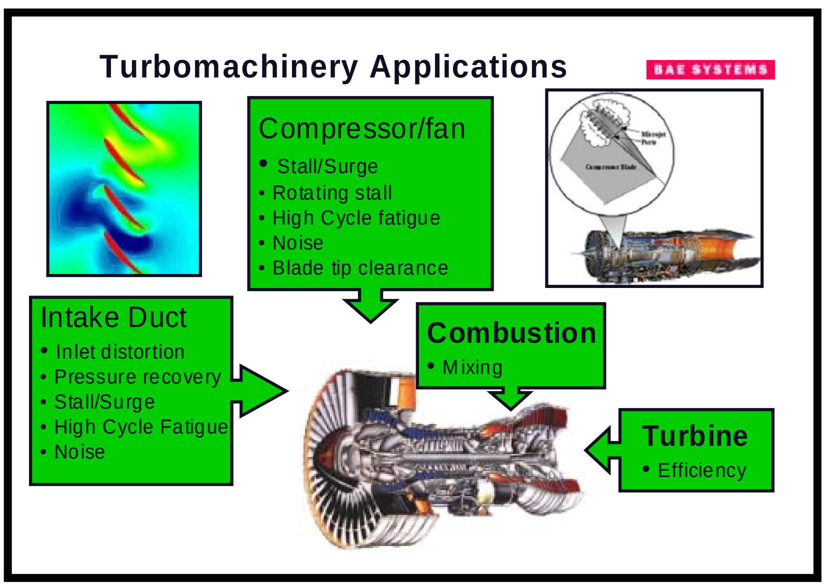
Modify local surface pressure gradient to promote/delay separation

Detect separation line position → modify separation line → Modify vortex → Manoeuvre vehicle

Gryphon MEMS Controlled UAV (UCLA)

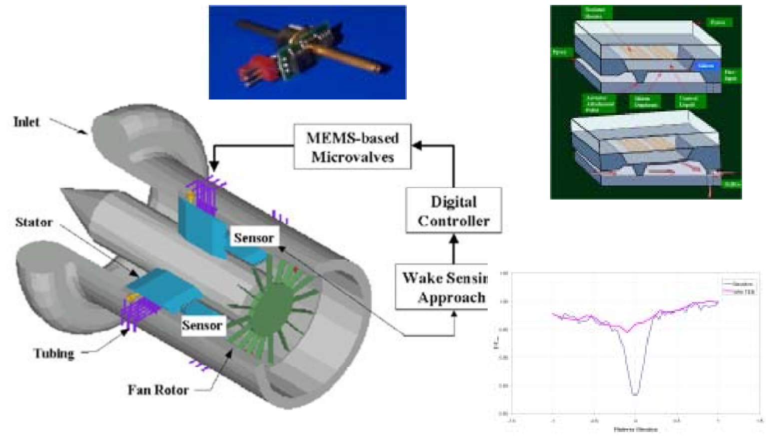



MEMS to Control Smart Projectile
BAE SYSTEMS
MEMS Flight Control for Projectiles
ARL Computational Fluid Dynamics Codes
• Understand basic aerodynamic characteristics for flow control
• Investigate "where" jets could be placed for various effects
0.720
0.716
0.712
0.709
0.705
Pressure Contours
40mm Grenade, M = 0.25
Expanded View of Synthetic Jet from GaTech
PIV Data of Modulated Microjet Array
40mm HE/PD M203
ARL
Weapons and Materials Research Directorate
MTO
DARPA
Microsystems Technology Office
Approved for Public Release - Distribution Unlimited


Turbomachinery Applications
BAE SYSTEMS
Compressor/fan
• Stall/Surge
• Rotating stall
• High Cycle fatigue
• Noise
• Blade tip clearance
Intake Duct
• Inlet distortion
• Pressure recovery
• Stall/Surge
• High Cycle Fatigue
• Noise
Combustion
• Mixing
Turbine
• Efficiency

Active Noise Control

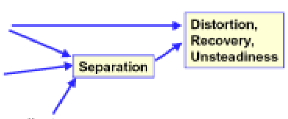
BAE SYSTEMS

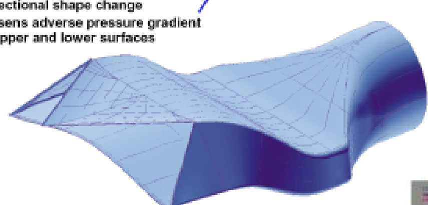


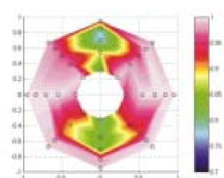
Suppression of Intake Distortion

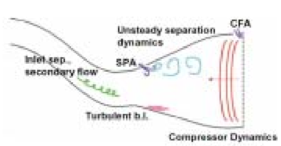
BAE SYSTEMS

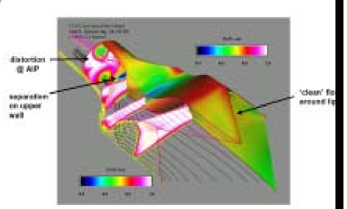
- Turns
  - Introduce secondary flows
- Diffusion
  - Adverse pressure gradient
- Cross-sectional shape change
  - Worsens adverse pressure gradient on upper and lower surfaces



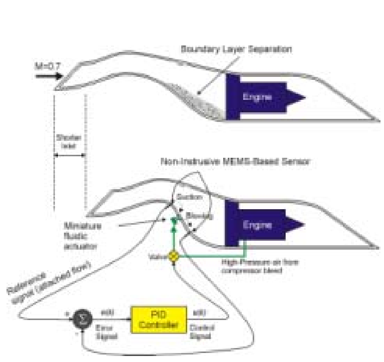


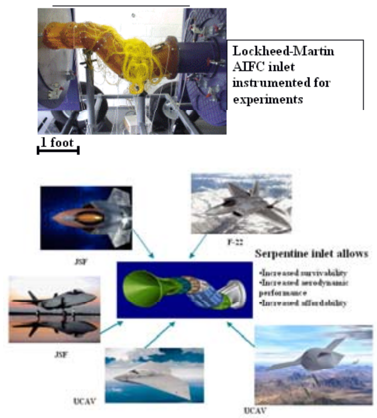




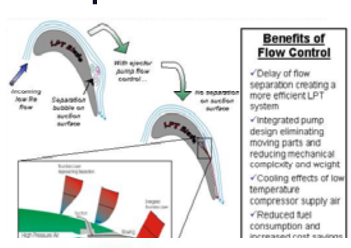


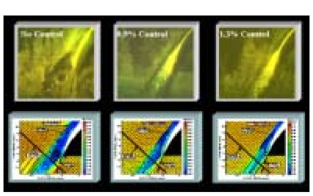
Separation Control in Intake Ducts

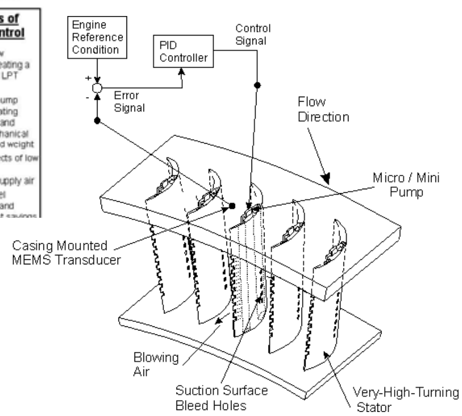


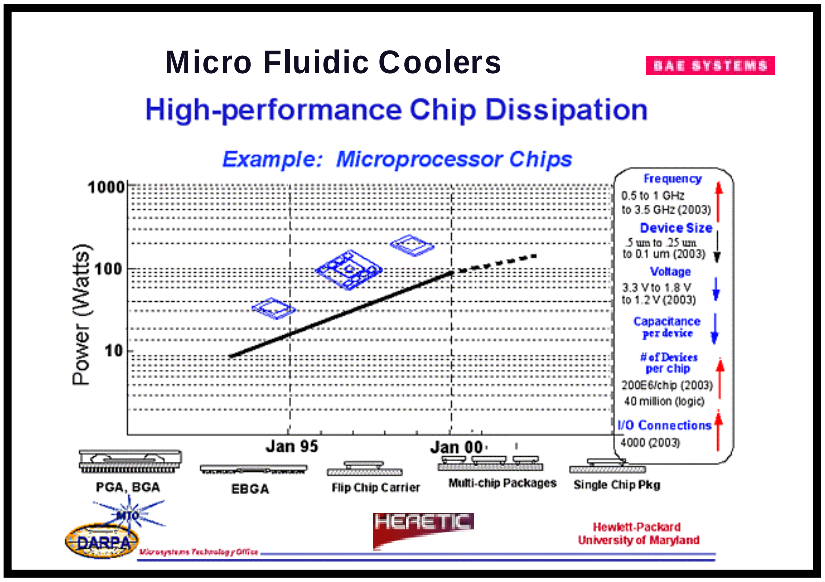


Separation Control on Cascade

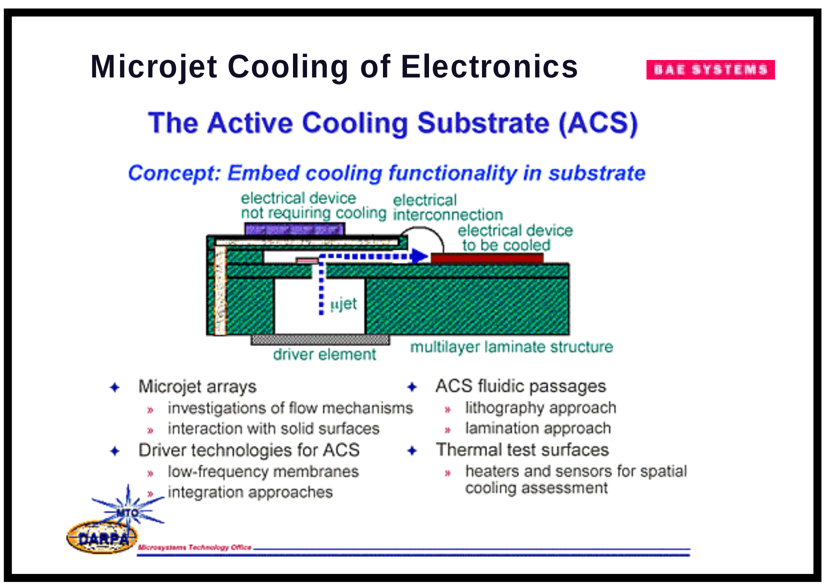




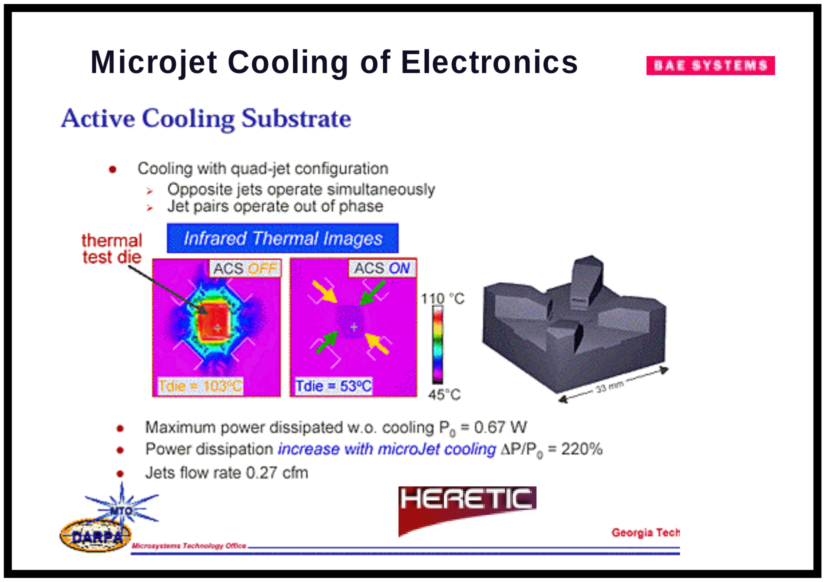


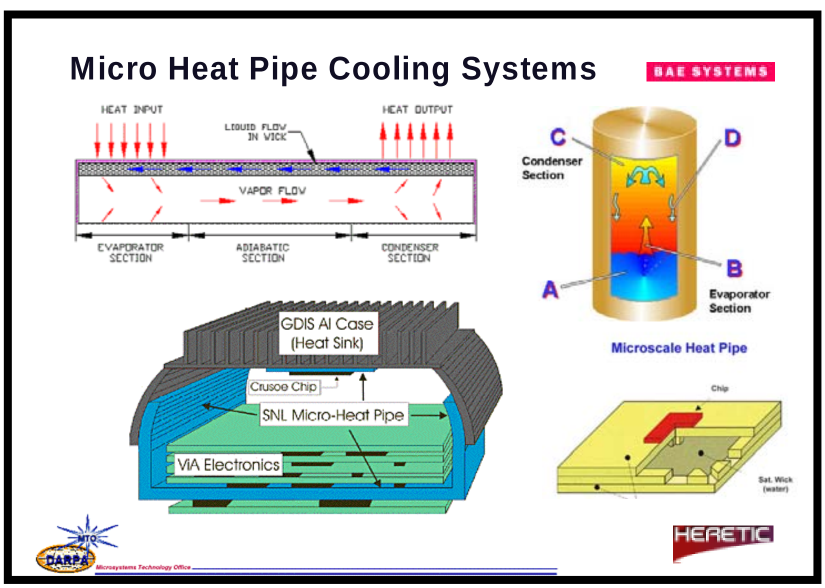


Micro Fluidic Coolers
BAE SYSTEMS
High-performance Chip Dissipation
Example: Microprocessor Chips
1000
100
10
Power (Watts)
Jan 95
Jan 00
Frequency
0.5 to 1 GHz
to 3.5 GHz (2003)
Device Size
.5 um to .25 um
to 0.1 um (2003)
Voltage
3.3 V to 1.8 V
to 1.2 V (2003)
Capacitance
per device
# of Devices
per chip
200E6/chip (2003)
40 million (logic)
I/O Connections
4000 (2003)
PGA, BGA
EBGA
Flip Chip Carrier
Multi-chip Packages
Single Chip Pkg
MTO
DARPA
Microsystems Technology Office
HERETIC
Hewlett-Packard
University of Maryland



Microjet Cooling of Electronics
BAE SYSTEMS
The Active Cooling Substrate (ACS)
Concept: Embed cooling functionality in substrate
electrical device
not requiring cooling
electrical
interconnection
electrical device
to be cooled
µjet
driver element
multilayer laminate structure
Microjet arrays
» investigations of flow mechanisms
» interaction with solid surfaces
Driver technologies for ACS
» low-frequency membranes
» integration approaches
ACS fluidic passages
» lithography approach
» lamination approach
Thermal test surfaces
» heaters and sensors for spatial
cooling assessment
MTO
DARPA
Microsystems Technology Office


Microjet Cooling of Electronics
BAE SYSTEMS
Active Cooling Substrate
• Cooling with quad-jet configuration
➢ Opposite jets operate simultaneously
➢ Jet pairs operate out of phase
thermal test die
Infrared Thermal Images
ACS OFF
ACS ON
Tdie = 103°C
Tdie = 53°C
110 °C
45°C
33 mm
• Maximum power dissipated w.o. cooling P_0 = 0.67 W
• Power dissipation increase with microJet cooling $\Delta P/P_0$ = 220%
• Jets flow rate 0.27 cfm
MTO
DARPA
Microsystems Technology Office
HERETIC
Georgia Tech


Micro Heat Pipe Cooling Systems
BAE SYSTEMS
HEAT INPUT
LIQUID FLOW IN WICK
HEAT OUTPUT
VAPOR FLOW
EVAPORATOR SECTION
ADIABATIC SECTION
CONDENSER SECTION
C
D
Condenser Section
B
A
Evaporator Section
Microscale Heat Pipe
GDIS Al Case (Heat Sink)
Crusoe Chip
SNL Micro-Heat Pipe
VIA Electronics
Chip
Sat. Wick (water)
MTO
DARPA
Microsystems Technology Office
HERETIC

Robustness Considerations

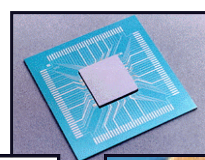
BAE SYSTEMS

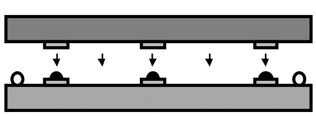
- Traditional MEMS remote from environment
  - Single or small arrays
  - Hermetic packaging
- Flow control $\Rightarrow$ must interact directly
  - Harsh environments
  - Reliability
  - Maintenance & repair
  - Safety and certification
  - Large arrays of integrated devices
- Severe implications on design and packaging

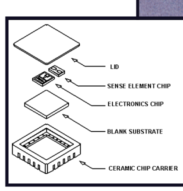
Packaging

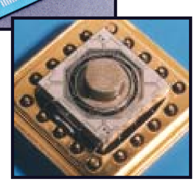
BAE SYSTEMS

- Science/art of establishing interconnections and operating environment
- Affects: Cost, Performance, Reliability
- Up to 80 - 95% of Cost
- Unique for each application
- Product “Make or break”









Conclusions

BAE SYSTEMS

- First Industrial Applications of MEMS
  - Limited numbers of sensors and actuators
  - Cover small, localised surface areas
  - Limited intelligence (simple on-off)
  - Flow separation (manoeuvre, or high lift improvement)
  - Small UAVs
- Substantial advances required to achieve large surface area reactive skins
  - Fluid physics
  - Process technologies to fabricate devices that are:
    - Robust, Affordable, Reliable