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14. ABSTRACT
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Report Title

Final Report: Active Flow Control Technologies -- Tools, Applications and Transition

ABSTRACT

A workshop entitled Twenty Years of `Modern' AFC, What Next? (Tools, Applications and Transition: What, Where and How?) was held on October 26-27, 2015 at the Florida Center for Advanced Aero-propulsion, AME Building, Florida State University in Tallahassee, Florida. The workshop was attended by active members of Department of Defense such as AFOSR, ARO, ONR, AFRL, ARL and Aerospace Industry including Boeing, Lockheed Martin, Northrop Grumman as well as many International flow control experts. A total number of 18 invited talks were delivered under three sessions and multiple group discussions were held to highlight Active Flow Control (AFC) technologies, examples of successful industrial applications and the challenges associated in transitioning AFC technologies to aerospace applications.

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Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
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Total Number:	

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This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:	0.00
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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Final Report on the Workshop Entitled:

Active Flow Control Technologies - Tools, Applications and Transition

by

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(December 17, 2016)

1 Active Flow Control Workshop

A workshop entitled **Twenty Years of 'Modern' AFC, What Next? (Tools, Applications and Transition: What, Where and How?)** was held on October 26-27, 2015 at the Florida Center for Advanced Aero-propulsion, AME Building, Florida State University in Tallahassee, Florida. The workshop was attended by active members of Department of Defense such as AFOSR, ARO, ONR, AFRL, ARL and Aerospace Industry including Boeing, Lockheed Martin, Northrop Grumman as well as many International flow control experts. A total number of 18 invited talks were delivered under three sessions and multiple group discussions were held to highlight Active Flow Control (AFC) technologies, examples of successful industrial applications and the challenges associated in transitioning AFC technologies to aerospace applications. The workshop was jointly funded by ONR, ARO, Boeing, FSU and OSU.

1.1 Summary

Active flow control (AFC) for a wide array of applications has seen a surge of activity in recent years due to the potential for substantial gains in performance offered by flow control schemes. Subsonic applications range from controlling flow separation over aircraft wings to active control of flow over turbine and compressor blades/airfoils and active management of separation/flow distortion in engine inlets and S-ducts. In high-speed flows, control of flow oscillations in cavity flows, supersonic impinging jets and jet noise are areas where various active control methods can lead to dramatic gains. To establish the state-of-art and transformative technologies, lay path to transition and provide a discussion forum, the Florida Center for Advanced Aero-Propulsion (FCAAP), a multi-university state-sponsored center of excellence in collaboration with the Ohio State University hosted a AFC workshop. The meeting was held on October 26-27, 2015, at Florida State University in Tallahassee, Florida. Leaders from state, national, and international aerospace and aviation industries, academia as well as representatives from the government agencies gathered for in-depth discussions on the direction and future of active flow control. Another objective was to discuss impediments to transition from TRL1 to TRL6.

The symposium featured invited talks and posters describing the cutting edge research being conducted by our faculty, students, and scientists in partnership with industry and government agencies. Research and technology development projects discussed at the symposium included, Actuator and Sensor Design, Subsonic/Supersonic Flow Control, and Experimental and Simulation Tools for AFC. Applications of this research and technology can be found in the areas of aeronautics, aviation, aerospace, propulsion, and power. The workshop was very successful with an attendance of 70 people from ARO, AFOSR, ONR, AFRL, ARL, Boeing, Lockheed Martin, Northrop Grumman and many National and International flow control experts.

1.2 Covered Topics

The workshop covered a broad range of topics related to Active Flow Control with emphasis on technology transition. Some of the topics were: Actuator and Sensor Design, Subsonic/Supersonic Flow Control, and Experimental and Simulation Tools for AFC.

1.3 Venue Location and Dates

October 26-27, 2015 at Florida State University in Tallahassee, Florida.

1.4 List of attendees

The list of attendees is compiled in Tables 1 and 2.

2 Agenda

Day 1 (Monday, October 26, 2015)

8:00 Continental Breakfast & Registration (AME atrium)
8:30 Welcoming Remarks
8:40 Overview of the Workshop
8:50 **Keynote Talk I** - Active Flow Control – Lessons Learned
  D. Williams, Professor, Illinois Institute of Technology

9:20 Coffee Break

Session I: Tools I

9:30 Introduction/Goals for the Session
  L. Cattafesta, FSU
9:40 Formation and Evolution of Finite Span Synthetic Jets
  M. Amitay, Professor, Rensselaer Polytechnic Institute
9:50 Jet Based AFC - Applications, Opportunities and Challenges
  F. Alvi, Professor, Florida State University
10:00 Small Amplitude Perturbation based Flow Control using Plasma Actuators
  M. Samimy, Professor, Ohio State University
10:10 Non-Thermal Surface Plasma Actuators - Transition to Real Flight Demonstrator
  N. Benard, Associate Professor, Université de Poitiers
10:20 Fluidic-Based Flow Control Approaches
  A. Glezer, Professor, Georgia Institute of Technology
10:30 Panel Discussion

11:30 **Plenary Talk**: What Lies Ahead for Flow Control?
  D. Smith, Program Manager, Sea Based Aviation–Aircraft Science & Technology, Office of Naval Research

12:00 Lunch at AME Research Center

Session II: Tools II

1:30 Introduction/Goals for the Session
K. Taira, FSU
1:40 CFD Tools for Flow Control Simulations
R. Mittal, Professor, Johns Hopkins University
1:50 Open Challenges in Model-based Flow Control
C. Rowley, Professor, Princeton University
2:00 Sensor Technology for Flow Control
M. Sheplak, Professor, University of Florida
2:10 Linear Analysis of Turbulent Mean Flow Fields
T. Colonius, Professor, California Institute of Technology
2:20 Prospects for Bluff Body Feedback Control
R. King, Professor, Technische Universität Berlin
2:30 The A3XX Trailing Vortices, Seen from the Other Side of the Pond
V. Theofilis, Professor, Universidad Politecnica de Madrid
2:40 Use of High-Fidelity Simulations to Analyze Plasma-Based Flow Control
D. Gaitonde, Professor, Ohio State University
2:50 Panel Discussion

3:30 Coffee break (AME atrium)
3:45 AME/FCAAP Wind Tunnels / Facilities Tour

Session III: AFC Technology Transition

4:30 Introduction/Goals for the session
F. Alvi, FSU
4:40 Technical Challenges in Transitioning AFC Technologies
L. Centolanza, Rotors Technical Area Lead, AMRDEC, US Army
4:50 Barriers to Transitioning Flow Control Technologies
E. Whalen, Flow Control Actuators Manager, The Boeing Company
5:00 Role of Actuator Location for Control of Separated Flows in Applications
P. R. Viswanath, Senior Scientist, Boeing R&D India
5:10 The AFC Trial for Aerodynamic Drag Reduction using a Simplified Body
5:20 Increasing the Operation Map of Turbo Compressors by Active Flow Control
L. Sun, VP of R&D and Project Management, Danfoss Turbocor Compressors
5:30 Panel Discussion

6:15 Transportation to UCC
6:30 Reception at UCC

Day 2 (Tuesday, October 27, 2015)

8:00 Continental Breakfast (AME atrium)

8:30 **Keynote Talk II** - Successes and Impediments/Challenges in AFC Technology Transition
E. Whalen, Flow Control Actuators Manager, The Boeing Company

9:00 Recap of the Panel Discussions from Day 1

9:30 Coffee Break

9:45 Forum: Technology Demonstrators / Platforms / performance rubric
Moderators L. Cattafesta (FSU) & M. Samimy (OSU))
Group discussion: Challenges/solutions/opportunities in Technology Transition
Outcome: Platform / challenge problems
Guidelines for future research
Planning for Next AFC Assessment and Transition Meeting – Where, When

12:30 Lunch (AME Atrium) / Adjourn

3 Meeting Minutes

3.1 Section I: Tools I

M Amitay

- Synthetic jets have spanwise dependence
- The geometry of the synthetic jet has effect on the output
  Determined the optimal geometry: 200 m/s
- Learned vortex dynamics of synthetic jets through SPIV
- Found secondary structures in spanwise direction
- Applied to a swept wing:
  Less is more. Reduced the number of actuators increased performance

F Alvi

- Non-ZNMF actuators
  Steady vs. Unsteady
- Control and manipulate separation
  Both in internal and external flows
- High-speed flows:
  Supersonic Impinging Jet
  Cavity Flows
    Reduced tone levels in both with microjets
  Shock-BL interactions

- Microjets:
  - High subsonic to supersonic flow regimes
  - Lab scale testing and full scale testings
  - Low-pressure turbines and compressors

M Samimy

- Two classes of plasma actuators
  - Momentum based (AC-DBD)
  - Perturbation/thermal-based
- Perturbation/Thermal-based
- Local arc filament plasma actuators (LAFPA)
  - Localized applications
- Nano-second DBD actuators
  - Distributed applications
- Uses instability-based flow control
- Some flows have preferred modes
- Advantage:
  - Flow dynamics amplify small disturbances
- Examples:
  - Mach 1.3 Jet
    - Reduced tones and mixing control
  - Boeing VR-7
    - Reduced separation

N Benard

- Overview of how DBD works
- Metrics:
  - Ionic wind: O(10) m/s
  - Thrust: O(100) mN
  - Bandwidth: O(100) kHz
- Cost Metrics:
  - Electric power: O(100) W/m
  - Weight: O(10) g/m
  - Electric power per weight: O(1) W/g
- Configurations: Depend on the scale of the problem
- Examples:
  - Separation control
    - LE, Mid, and TE separation control
  - Turbulent boundary transition control
    - Both in lab and full-scale
- Numerical models:

    - High-Fidelity: Computational time is costly
    - Low-Fidelity: Time-averaged
    - LEM
    - Experimental-based models
    - Reduced-order models
- Transition to real flight testing
    - Altitude effects
    - Humidity effects
    - Heavy power supply (though can lower weight)
    - Durability
        - Dielectric not suitable for industry
    - Electromagnetic capabilities
    - Dusty environment

A Glezer

- Aerodynamic control
    - External and internal flows
    - Global modifications
    - Limits:
        - Flow separation
        - Attached flow
- Hybrid surface actuators
    - Reduce drag on airfoil
    - Modify pitching moment
- Separated flows
    - High-lift enhancements
        - Fluidic devices
    - Transition control
        - Spark jets?
        - Rotor-craft applications
- Attached/separated flows
    - Detached bleed
    - Modify lift coefficient (through reduction) without actuation
- High-speed flows
    - Indirect shock control
    - Can regulate shock location
- Path to implementation
    - Vertical tail of 757
- Overview of implementation:
    - Aerodynamic performances
        - Does it work?
    - Actuator robustness

Does it work outside the lab?

System integration

Can we implement it in industry

Panel Discussion

D. Williams

- Clarification of attached/separated flow

Raghu

- Are we confident with the physics/scaling issues of the flow

  Glezer: Sometimes we don't understand why it works, but accept that it still works. Reference the Wright brothers

Raghu

- Best way of integration

  Ed: A lot of risk for integration in the design process

  Alvi: Tension between complexity and applicability of devices

  Samimy: Time-scales of aircraft design are very long, so it makes sense why they havent been implemented.

  Glezer: UAV time-scales may be a safe, low-risk intermediate step for full-scale application.
- How would AFC change the industry?

  Alvi: More efficient application of the science and systems we study

  Ed: Must be self-aware and know what the industry requires.

  Doug: There are applications outside of aerospace.
- Are the time-scales of the full-scale testing too long?

  Amitay: We have lowered time-scales by looking into the auto industry. Cars are easier to work with than aircraft.
- Momentum effects on Fluidic Devices?

  Amitay: It is a complex system and momentum is but one factor or metric to consider. Also includes vortex dynamics, etc.

  Lou: Its an iterative process. We dont get it right on the first try.

Lou

- Do we have sufficient Design Tools?

  Glezer: Are we looking for correlations? Cmu? Actuators are very application specific.

  Doug: Will we need a wide range of tools? There is a process. We dont start with CFD. We start with sketches, intuition, and design.

Samimy: AFC is a tough problem. We have tools for specific problems, but not blanket tools.

Raghu: In non-aerospace applications, cost is a large factor in non-aerospace applications.

Tim

- How about feedback control? Everything was open-loop.

  Glezer: Closing the loop is not a large problem. Surely not trivial, but it is tractable.

  Alvi: Closed-loop results werent much better than steady

Alvi

- What are the metrics industry needs?

Raghu

- Are these the best actuators we have?

  Amitay: It's very application specific. There isn't a blanket actuator that does everything.

  Glezer: There is a future of unknown actuators still to be designed.

  Amitay: Industry should approach academia to discuss problems.

Doug Smith

- What lies ahead for flow control?
- Distinction between basic science and technological innovation
  - Basic Science: Academia
  - Technological innovation: Industry
- Value of AFC?
  - Understanding fluids
    - In particular, unsteady fluids
  - More computational capabilities
  - More technologies (lasers, etc.)
  - Build upon current rules of thumb
    - Use AFC to go beyond them.
  - Actuators design charts are a thing.
- Addressing student legacy
- Find the real program manager
- Talk about sustainment of science and technology
- Fluid mechanics is universal across multiple disciplines. So should active flow control
- Flow control at atmospheric microscale?

- What happened to micro-actuators/MEMS?
  Dave: MEMS sensors are awesome and will bring a large aspect and tool for flow control
- Sam: AFC be design-based rather than corrective?

3.2 Section II: Tools II

R. Mittal

1. Introduction
   (a) Previous session Tools-I laid the foundation and made the job easier for the Tools-II session
2. Synthetic jets
   (a) Using them for separation control
   (b) Large range of frequencies
   (c) Inherent complexity
   (d) Used to reduce separation and understand physics associated with larger L/D.
   (e) As an aerodynamic designer- what are we looking for? Do we have the knowledge and tools to answer questions? The solutions should be rapid and reliable and prediction becomes important including computational tools, shape, size, "unknown unknowns".
3. Complicated physics
   (a) Characteristic vs. jet frequency are not monotonic, complicated lift and drag actuation characteristics
   (b) Significant variance in control authority
   (c) Effective F^*, C_μ
   (d) Predict variability
   (e) Global interactions and global response
   (f) Flow physics of synthetic jet (local interaction)
   (g) Other factors like slot geometry, compressibility effects, location, waveform, forcing frequency, momentum coefficient.
   (h) Is vorticity flux, C_μ the metric to match?
4. Insights
   (a) Key ZNMF (zero-net mass flux) parameters and using non-dimensionalization

(b) Matching Strouhal number is key
(c) Dominant parameter is jet strouhal number
(d) Vorticity flux is next level of quantity that you need to capture for flow control.
(e) Interaction is highly nonlinear
(f) Flow jumps from one lock-on frequency to another and output is not smooth
(g) Driving flow from natural to desirable limit cycle or one lockon state to another
(h) Designing simpler models to model global and local interactions
(i) Lots of “unknown unknowns”.

C. Rowley

1. Introduction
   (a) Lots of open challenges
   (b) Tried to answer open questions ”What are the suitable models for feedback control?”
2. Available tools
   (a) Linearized models
   (b) Balanced POD and Balanced truncation
   (c) System ID
   (d) Control-Linear controllers, PID, optimal control
3. Challenges-POD model
   (a) Low-energy modes are important for dynamics
   (b) Failure of POD model, example: Channel flow
   (c) Transient growth not captured by just the most energetic POD modes.
   (d) Demonstrates fragility of POD model
   (e) Low energy modes can be be important for dynamics
4. Better model
   (a) Balanced POD-much more reliable
   (b) Characterizing sensitivity and observability (states with largest influence on dynamics)
   (c) Eigenvalue Realization Algorithm (ERA)

(d) Can be used for control design
(e) Use of linear controller to stabilize vortex shedding

5. Sensor/Actuator placement

   (a) Naive view point: Placing actuators where flow is most sensitive
   (b) Ginberg-Landau model problem
   (c) Delays are important feature of convection (feedback)
   (d) Solve H_2, for different actuator sensor locations
   (e) Gradient-based method to optimize locations

6. Insights

   (a) Switched linear models as parameter varies
   (b) Using Dynamic mode decomposition (DMD) with inputs
   (c) Gain scheduling, sinusoidally varying angles
   (d) Koopman operator
      i. Useful for determining invariant manifold
      ii. Change of coordinates to straighten to a linear system
      iii. Diagonalizing nonlinear system to get a linear system
      iv. Pick basins of attractions to give phase dynamics in each basin
   (e) Shear layer separation bubble for nonlinear systems

M. Sheplak

1. Introduction

   (a) Thanked Boeing for helping transition stuff out of the lab to real world

2. Overview and concerns

   (a) Ideal systems vs. reality
   (b) Idealized feedback loop
   (c) Not accounting for sensor dynamics
   (d) Nonlinearities generating harmonics
   (e) Instrumentation issue

3. Sensor design

(a) Non-intrusive
(b) Gain-phase relationship-would like it to be linear
(c) Don't want an everything sensor
(d) Want a calibration sheet good for 20 years
(e) Is it possible use existing technologies?
(f) Don't want to over-engineer system - may not be necessary.

4. Challenges, Prospects and Insights

(a) Commercial off-the shelf (COTS)- $100,000$ dollars
(b) Various types of sensors, LDV, PIV, CTA, hot-films
(c) Moist environment, frost issues associated with dynamic pressure sensors
(d) "Cheap" pressure sensors, Research sensors-MEMS? We tell program managers regarding single digit dollars to manufacture them.
(e) Though Ho (1998) had lot of the issues solved, stuff never made it outside lab, nobody believed them for a long time.
(f) Ho hasn't been in this field for 15 years
(g) Plateau of productivity
(h) Need to understand relevant dynamics leverage existing technologies
(i) Need to transition outside lab
(j) Piezoelectric microphones
(k) Transition to companies -large or small variety
(l) MEMS still has hope but remains immature

T. Colonius

1. Introduction

(a) Talk closely related to Clancy Rowley's talk
(b) Push linear models for high Reynolds number flows
(c) Understand instabilities of underlying shear flows

2. Overview

(a) Computations have been ubiquitous, computers do things that we could only dream about
(b) 2D and 2D eigenvalue problems are possible nowadays

(c) Strictly applicable to low Reynolds number flows
(d) High Reynolds number flows case-no rigorous theory

3. Modeling
   (a) Large scale coherent structures
   (b) Computational shortcuts
   (c) Large global flow calculation

4. Approach
   (a) Classic Reynolds decomposition
   (b) Reynolds averaged NS equations
   (c) Characterizing fluctuations about mean flow and triadic interactions
   (d) Eddy viscosity model retaining nonlinear terms
   (e) Use knowledge about linear non-normal operator
   (f) High Reynolds number calculations and jet flows

5. Analysis tools and insights
   (a) Resolvent mode analysis-identify highest gain mode
   (b) Analyze LES data
   (c) Empirical resolvent modes, also in turbulent flows
   (d) PSE computation for predicting (high gain) resolvent modes
   (e) PSE deals with weakly non-parallel flows (One-way Euler/NS solvers)
   (f) Answers to why linear theory works?

R. King

1. Introduction
   (a) Fundamental flow control research
   (b) Tackling flow control research
   (c) Uncertainty coming from disturbances and why we do closed-loop control
   (d) Cross-wind effects

2. Overview
   (a) Active flow control-cross wind running over model
   (b) Unsteady aerodynamic effect

   (c) Unsteady mechanical effect
   (d) Turning of ground vehicle due to cross-winds
   (e) Input in a mathematical model of real car including a driver
   (f) Net effect by steering to model them (bluff body control)

3. Approach and Insights
   (a) Closed loop control is more than just a hardware
   (b) Worked on Galerkin-POD model
   (c) Conservative models - hammerstein compensation
   (d) Control- conservative controller
   (e) Parameterized linear mdoels- linear parameter varying control which are less conservative
   (f) Best control models are a combination of open and feedback control
   (g) Input-output behavior and estimate cycle force

V. Theofilis

1. Introduction
   (a) Tale of 2 cases on treatment of science in technology

2. Overview
   (a) Airports charge airline companies by the time their planes make others wait in line
   (b) Destruction of trailing vortices is crucial for airplane makers.
   (c) Issue of trailing vortex of aircraft that is heavier than jumbo, airlines would lose its shine
   (d) Super heavy weight of A3XX may not be a good idea.

3. Insights
   (a) Instabilities can be used to destroy coherence structures of trailing vortices
   (b) Can we use instabilities to destroy trailing vortices?
   (c) The good (Boeing), the bad (Airbus) and the ugly (lawyers)
   (d) Good-Modal eigen analysis, non-modal transient growth analysis, short-term perturbations and interference with vortex system. Non-modal instabilities wins race if triggered appropriately.
   (e) Bad-Wishbone-altered vorticity-project - patented

(f) Experiments- rectangular blades, stick wishbone in there for given vorticity distribution

(g) Airbus: Super Heavy - A380 sole occupant,

D. Gaitonde

1. Introduction

   (a) Why LES? To capture spatial-temporal scales.

   (b) Since 2D LES is not accurate

   (c) RANS will remain the most important mean

2. Overview

   (a) ns-DBD: volume based model

   (b) ns-DBD: heating time that the flow that responds to is fast

   (c) Instantaneous heating

   (d) Empiricism when it comes to modeling actuator

   (e) Calculate force field and transfer force onto airfoil

   (f) All smaller scales we actually get rid off

   (g) Use of DMD to characterize effect

3. Insights

   (a) Empirical excitation model

   (b) LES shows that you end up generating flapping mode

   (c) Keep working with Mo Samimy to figure out the detailed structure

   (d) Manipulate the heads of the pins and structures generated by actuators-vortical structures, wall-bounded flow

   (e) High frequency excitation might be the way to exploit instabilities

   (f) CFD-experimental thrusts

Panel discussion

1. **Whalen**: When conducting flow control experiments, what can, or what should we measure in a reasonable way? What measurements should be taken to help flow control design? Since detailed PIV measurements are expensive, can we just do pressure measurements? How do I design my experiment to study effect of active flow control in a general? What are the rules of thumb? What do we need to measure to get a performance effect? **Colonius**: Lab setting study economical flow, practical situation.

We should verify that we are dealing with the same physics. It is difficult to answer that directly. Depends on if you want to understand full flow field or what parameter do you want to understand. **Samimy**: Can industry specify what they want to know/do about flow control. What type of pressure or surface stress measurements should I use to apply to industry, that is important transition to look at. **Colonius**: We should use our intuition for understanding, fundamental input-output relationships. **Rowley**: Where is the best place to put sensors, if you want to reconstruct the full information. **Mittal**: Do we have a uniform solution to modeling, too many combination of too many things happening. CFD validation workshop? Common two problems; can we predict the control of these flows? Galerkin, DMD based tools, very vast space of problems, two or three key problems and identify questions about those problems

2. **Cattafesta**: How important is the bias on success stories. Example from failure of POD-balanced POD. As a community we can learn a lot from mistakes. **Mittal**: This bias extends to all science, not only to AFC. **Samimy**- Failed efforts on flow control plasma actuation research, we learned a lot. Why not let people know. – May be an issue beyond flow control community.

3. **Alvi**: Mark is the only sensor person. Why is that so? **Sheplak**: People nowadays are only interested in pressure but not other quantities. Funding is a problem. Think about developement of LDV, PIV. Any of the stuff that makes it to industry takes $5-10$ years to industry. Actuators are sexy because there are interesting flow physics when examining the actuation-flow interactions. Sensors can be independent of flow physics. Actuators have a longer time lag. Was there a conscious decision to take sensor off the funding list? If there is a need for sensing, flow control community have to drive it and make it sexy. Fundamental scientific work, scientific exploration only, then it stops there. 8000 dollars of expense in that sensing box. You can make something cheaper. Does that give you additional information? Need for daring flow control experiments. **Rowley**: What disturbance is going to create ideal growth (Schmid). Does these computational tools be applicable to sensing technologies? **King**: fluidic is good with frequency and not with phase. Can we get independent control of amplitude, frequency, and phase? (as well as efficiency?) **Samimy**: Changing amplitude is hard. We can give you two out of the three things

4. **Cattafesta**: We do baseline, open and then feedback at the end. What do you feel about the order? **King**: Starting with open loop is better. Closed loop control without doing a lot of characterization. I can do closed loop with a couple of experiments. What we do is use solenoid valves. **Alvi**: We are dominated by fluid dynamicists in flow control. Control side vs. fluid dynamics. **King**: Only few control guys looking at flows. Control guy has to learn fluids. **Alvi**: Funding control vs. fluids faculty. **Smith**: No bias whatsoever. Flow control requires many disciplines. Things tend to be expensive for larger program. You could fund one grant but thats risky as a program manager and we do whatever we can.

5. **Rowley**: We are talking about flow control. We should be talking about modern flow control. Going the next step is important: machine learning control, cyber-physical system? **Taira**: There were encouraging results shown that extends linear control or analysis my encapsulating nonlinearities with Koopman analysis, mean flow analysis, control design. **Theofillis**: It's about analyzing flow from different perspectives, finding clever ways, its not automatic to extract information at the speed that you want. **Sun**: The fundamentals are the same, mathematics should be the common language, fluid control, degree of freedom, controllability , observability. Modal condensation is important. **Taira**: Do real time control for fluid systems is much harder due to associated high-dimensional degrees of freedom. **Sun**: You don't have to control everything. **Colonius**: There is a complicated interplay between numerics and computers. large linear system - transient growth.

3.3 Session III: AFC Technology Transition

L. Centolanza

- Rotorcraft applications may include on-blade, on-hub, on-fuselage, and interactions
- Haven't settled on AFC technology
- TRL current at 3 and target is reach TRL 6 (full scale environment)
- TARGET: REDUCE HUB DRAG ON FULLSCALE
- AFC technology requirement: Durable (all weather), maintainable (repair, inspect), reliable (fail safe), affordable (*qualification testing*, sustainable costs)
- Lack of CFD data for validation of fullscale tests, identify scaling parameters

E. Whalen

- Cannot design AFC solution for a given application w/o investment in simulation and testing and, capability to trade the technology (passive vs. active, vehicle aerodynamics)
- TRL may be high, but what about MRL (manufacturing) or IRL (integration) capabilities?
- AFC Requirements:
  - are the air/electrical requirements (that feed AFC devices) available on the aircraft
  - maintenance of AFC
  - working environment
  - manufacturing challenges: do we have a supply chain that can produce AFC devices
  - *Noise:* need effective and quiet actuator
- Integrate AFC as part of vehicle design and not an added feature

P. R. Viswanath

- Effectiveness of AFC: location of actuator is a key parameter
- Steady blowing upstream or downstream of separation location
- Separation control strategies: (1) energizing the B.L. upstream of separation, (2) Alter bubble flow, (3) Excite shear layer receptivity by unsteady actuation, (4) influence shear layer

L. Sun

- IGV is a mechanical way of controlling fluid flow
- Enhance operation envelope in centrifugal compressors: IGV, IntraFlow^{TM} technology (open and closed loop control), microjets (due to simplicity and effectiveness)
- Idea's of AFC come from universities (low TRL's) → institution + industry TRL 3 → Industry R & D TRL 5

Gary Dale

- Summary of "Flow Control: Challenges and Barriers to Technology Transition" from AIAA Dallas Meeting July 2015
- Need to have application in mind even for low TRL - creates a body of literature that can be used by others
- Mid TRL: actuator parameters such as spacing, power/air requirements
- High TRL: flight test with AFC system, safety, CLEEN technology
- Robust designs: trade studies, form a business case to engage customer
- Road blocks: MRL (manufacturing readiness level) and IRL (integration)
- Applications: Aero-optics − beam distortion control and Landing gear − noise reduction
- AFC penalties: weight, power/air requirements, cost to benefit study
- Possible road blocks: technology maturation, manufacturing issues, and stability of product (customer engagement)

4 Outcome

The workshop was very successful and well attended by AFC experts from various Government organizations, Aerospace Industry and Academia. We reviewed and identified the state-of-the-art in AFC, compared promising tools and technologies in terms of their performance and application, and the challenges in transitioning AFC to real applications. As a follow on to this workshop, two discussion groups were organized at the AIAA SciTech 2016 to identify the challenge problems in subsonic and supersonic flight regime. In continuation, ONR and NAVAIR organized another workshop on the use of AFC.

Name	Affiliation
Kareem Ahmed	Univ Central Florida
Farrukh Alvi	Florida State Univ
Michael Amitay	Rensselaer Polytechnic Inst
Nicolas Benard	Univ Poitiers
Laurent-Emmanuel Brizzi	Univ Poitiers
Steven Brunton	Univ Washington
Louis Cattafesta	Florida State Univ
Louis Centolanza	US Army
Emmanuel Collins	Florida State Univ
Tim Colonius	California Inst Tech
Daniel Cuppoletti	Northrop Grumman
Gary Dale	Air Force Research Lab
Erik Fernandez	Univ Central Florida
Datta Gaitonde	Ohio State Univ
Mark Glauser	Syracuse Univ
Bryan Glaz	Army Research Lab
Ari Glezer	Georgia Tech
Ebenezer Gnanamanickam	Embry-Riddle Aero Univ
Vladimir Golubev	Embry-Riddle Aero Univ
Sivaram Gogineni	Spectral Energies
James Gregory	Ohio State Univ
Christopher Harris	Northrop Grumman
Rudibert King	Tech Univ Berlin
Rajan Kumar	Florida State Univ

Table 1: Workshop attendees (list: 1 of 2).

Name	Affiliation
Jesse Little	Univ Arizona
Reda Mankbadi	Embry-Riddle Aero Univ
Rajat Mittal	Johns Hopkins Univ
Matthew Munson	Army Research Office
William Oates	Florida State Univ
Michael Ol	Air Force Research Lab
Surya Raghu	Advanced Fluidics
Clarence Rowley	Princeton Univ
Mo Samimy	Ohio State Univ
David Schatzman	US Army
Mark Sheplak	Univ Florida
Chiang Shih	Florida State Univ
Jurgen Seidel	US Air Force Academy
Douglas Smith	Office of Naval Research
Lin Sun	Turbocor
Kunihiko Taira	Florida State Univ
Vasillios Theofilis	Univ Politec Madrid
Mathew Thomas	US Army
Lawrence Ukeiley	Univ Florida
Miguel Visbal	Air Force Research Lab
PR Viswanath	Boeing India
Edward Whalen	Boeing
David Williams	Illinois Institute of Tech
Jacob Wilson	US Army
Rich Wlezien	Iowa State Univ
Oliver Wong	US Army

Table 2: Workshop attendees (list: 2 of 2).