Miniaturized Parametric Inlet Bleed Module with Integrated Discretized Flow Control

George Papadopoulos

Innoveering, LLC
Ronkonkoma, NY

9th Annual Shock Wave Boundary Layer Interaction (SWBLI) Technical Interchange Meeting (TIM)
May 24-25, 2016
Cleveland, OH

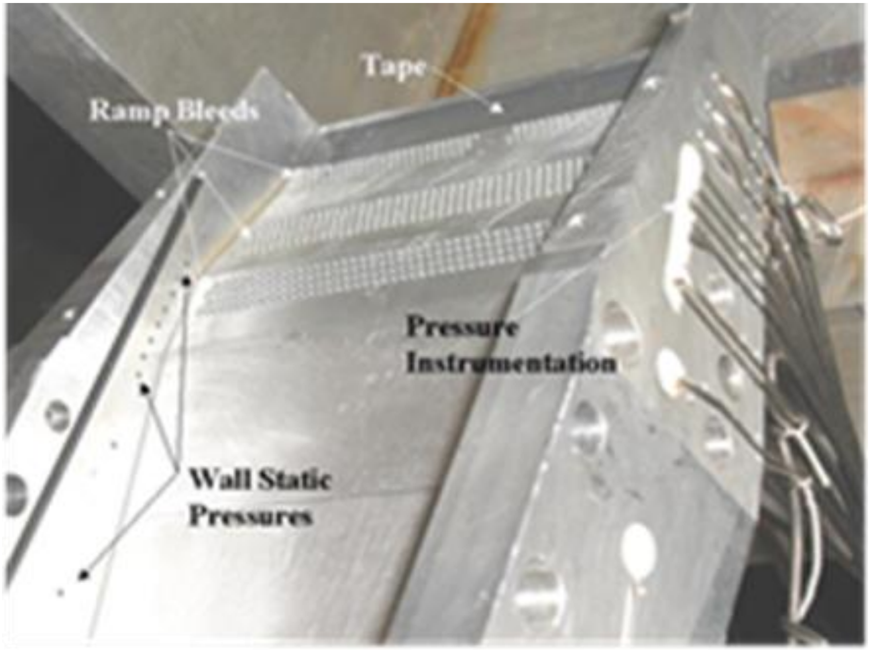
Background

Interaction of high Mach flow with aircraft and engine surfaces generates complex fluid dynamic phenomena that include shock waves, shear layers, vortices, and separated flows.

- inlet and isolator components must contain and stabilize the shock system.
- common technique to control the positioning of the shocks in these systems is through passive or active control of the boundary layers.
  - Boundary layer bleed can be used to control the thickness (and shape) of the boundary layer
  - Improves ability of BL to remain attached in the presence of shock/BL interactions.

Parametric Inlet Bleed

- historically been implemented by selectively filling or opening holes in plates with large arrays of holes
- Dental plaster and high-temperature silicone often serve as the fill material.
  - The process is manual, requiring significant tunnel downtime (as much as two days) to allow for the materials to cure.
  - fill material is also difficult to apply and remove successfully
  - Uncertainties in proper operation of bleed holes lead to repeat runs.



Needs / Factors driving Requirements

Key AF Need:

- Independent real-time regulation and flow metering of bleed holes that enables parametric bleed pattern implementation without the need for tunnel shutdown and model refurbishing.

Key Factors:

Factors	Description
Pressure Ratio	The ratio of the driving pressure on the flow side to the bleed plenum pressure that the design can withstand.
Flow Coefficient	The ratio of the mass-flow rate to the ideal mass-flow rate under choked conditions. A flow coefficient equivalent to a 90° bleed hole is desired for the respective *L/D* threshold and objective values.
Bleed Porosity	A measure of the total void areas to the total area of the bleed region.
Total Temperature	The total temperature of the flow which the parametric bleed system shall accommodate.
Turn Time	Measured as the time required to change one bleed pattern.
Flexibility	A measure of permutations of bleed patterns in a given parametric bleed system
Feasibility	The ease of integration of the parametric bleed system into a wind tunnel test model or test facility.

Micro-Parametric Bleed Interface (µPBI)

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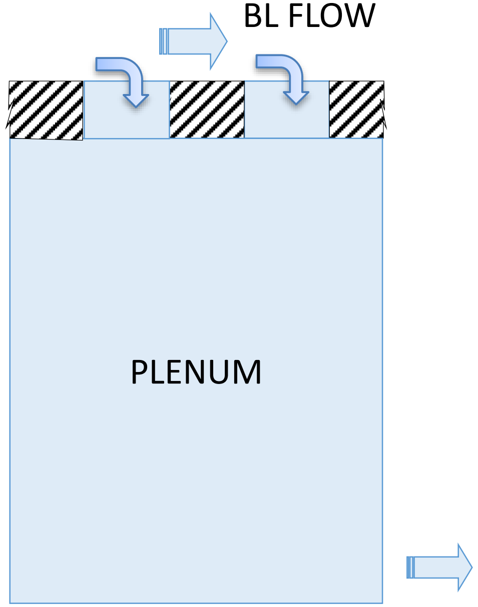
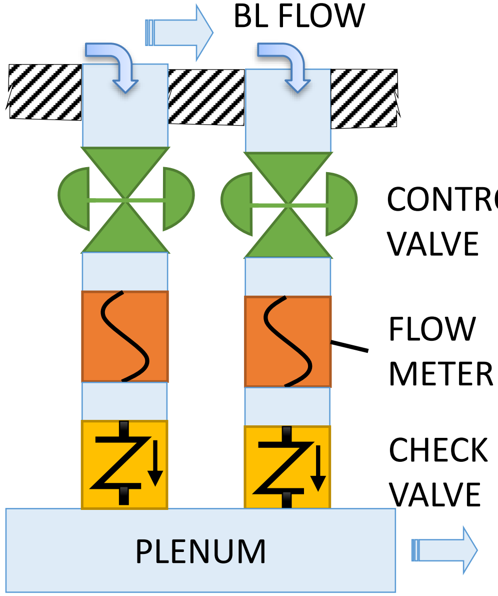
Proposed Approach:

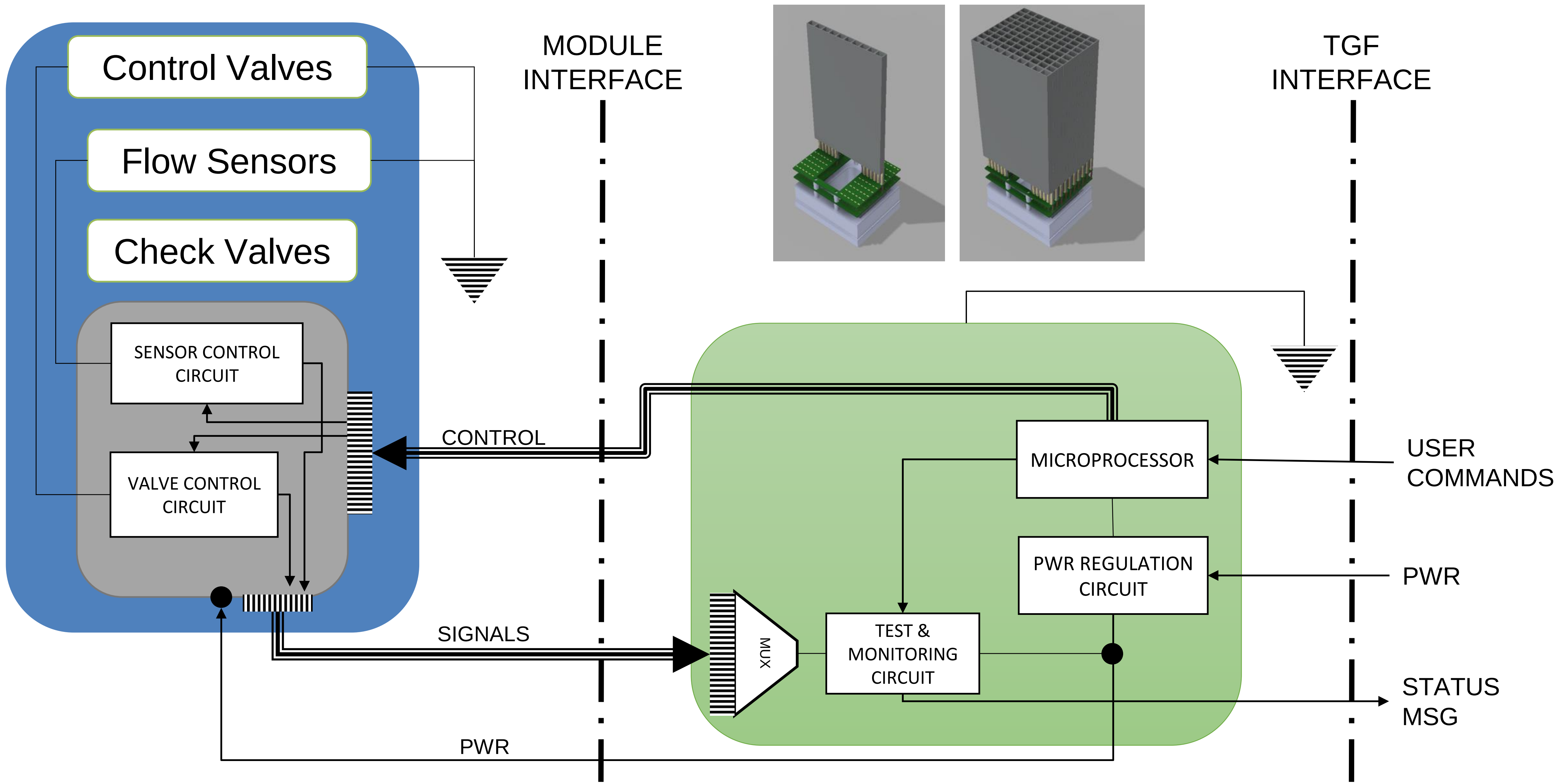
- Leverages MEMS design and fabrication processes enables efficient and cost effective development of an integrated bleed-hole module that incorporates discrete flow regulation and flow metering for each hole.
- Implements close-loop feedback control for each bleed hole to ensure desired response.
- Leverages advanced manufacturing methods (3D additive manufacturing) to fabricate modular and conforming packaging, specifically to address non-planar inlet surface implementations.



AF SWBLI Model	µPBI Approach
Stainless steel cover plate	Stainless steel cover plate
Each bleed zone connected to a plenum	Each µPBI unit has a common internal plenum
Vacuum total flow metered and regulated external to model	Vacuum total flow metered and regulated external to model
Parametric bleed pattern manually controlled	Parametric bleed pattern digitally controlled
Relative flow rate is NOT measured for each hole	Relative flow rate IS measured / controlled for each hole
Cross-talk between holes exists – no back flow protection	Back-flow protection; no cross-talk between holes



µPBI System Architecture



μPBI Integrated Unit

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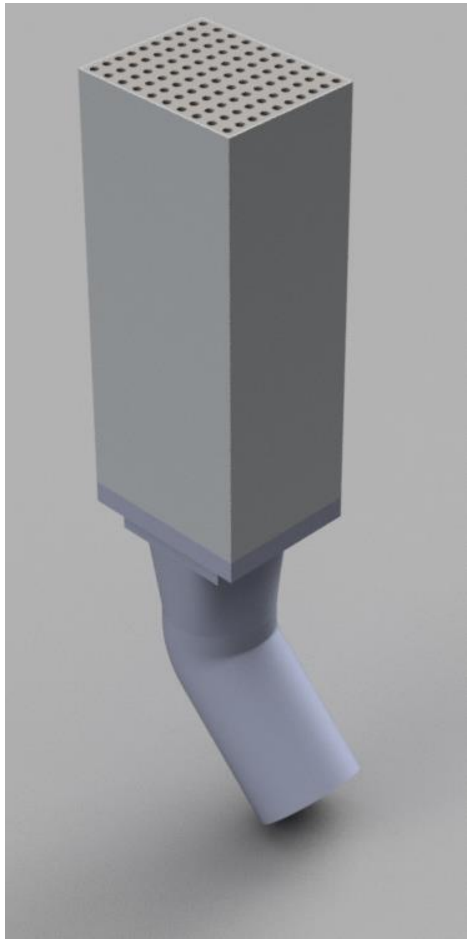
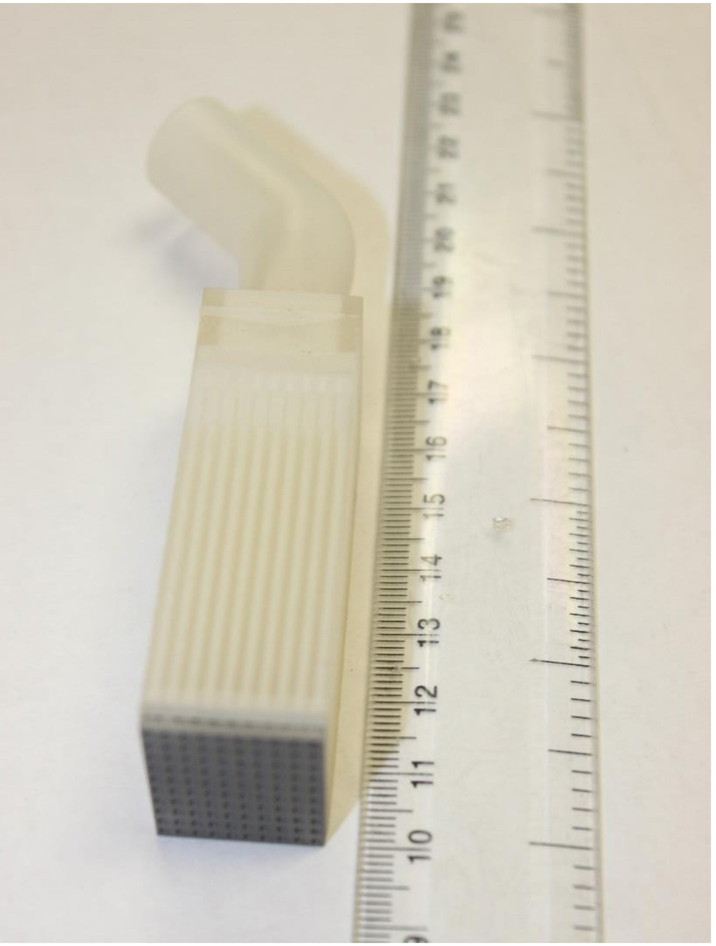
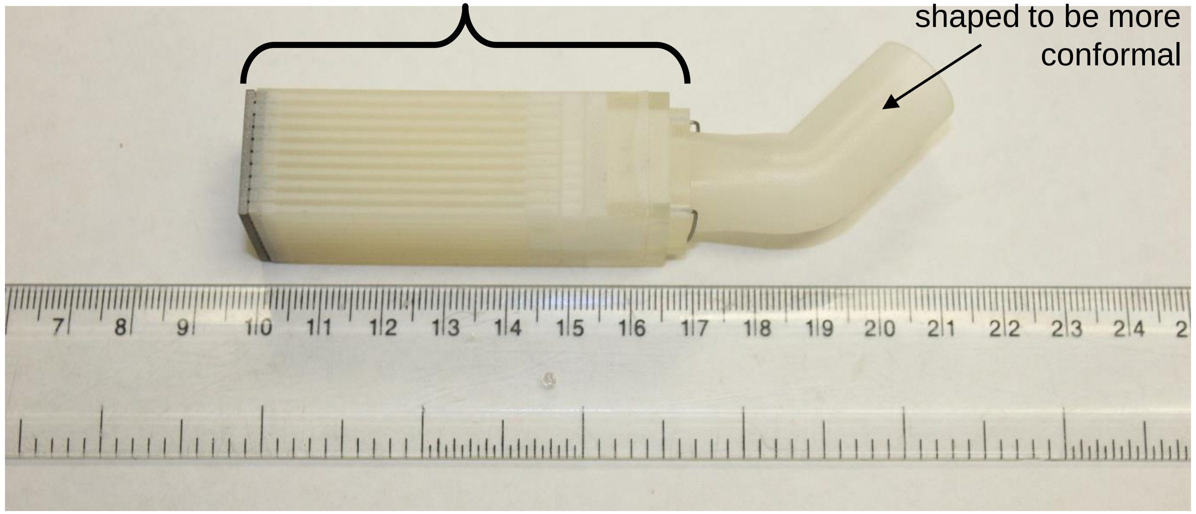
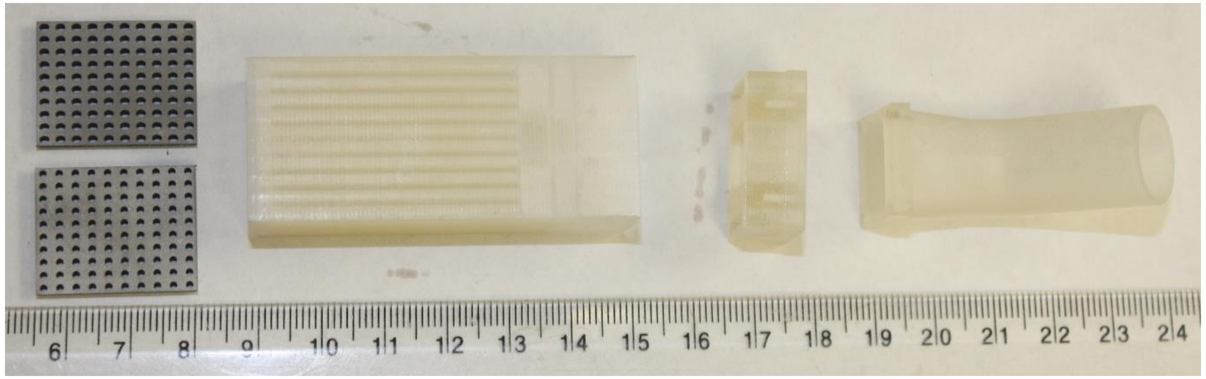




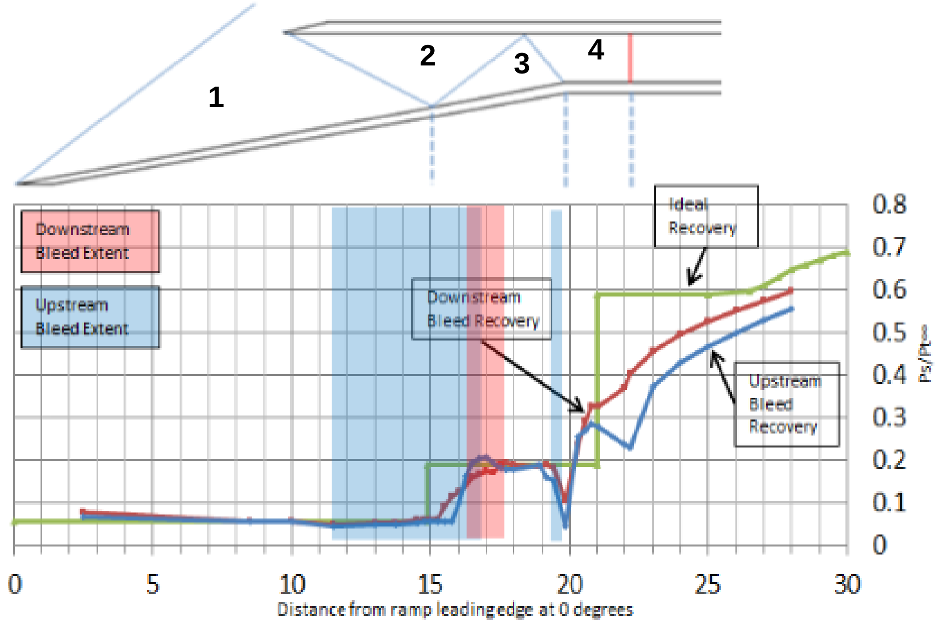
Length of Unit = 2.5 in

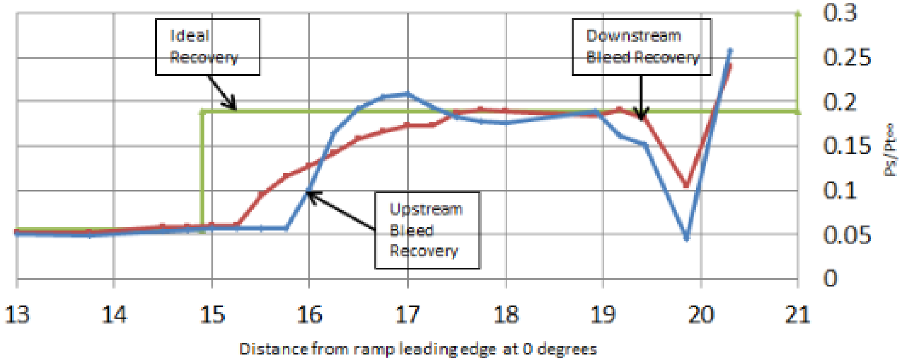
Hose adapter can be shaped to be more conformal

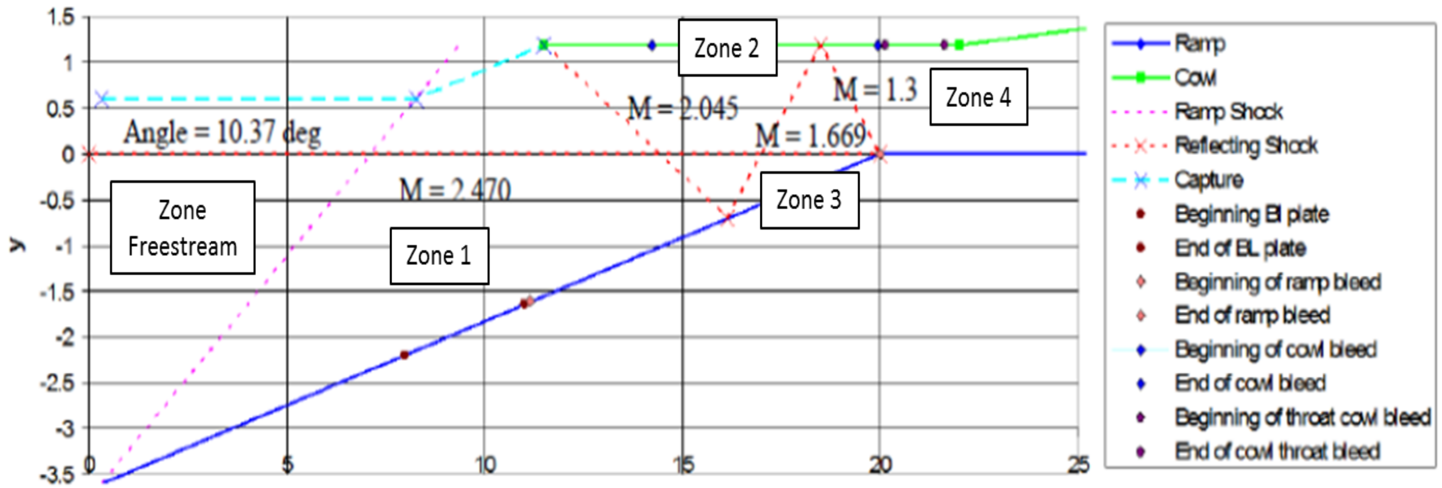




AF SWBLI Model Conditions

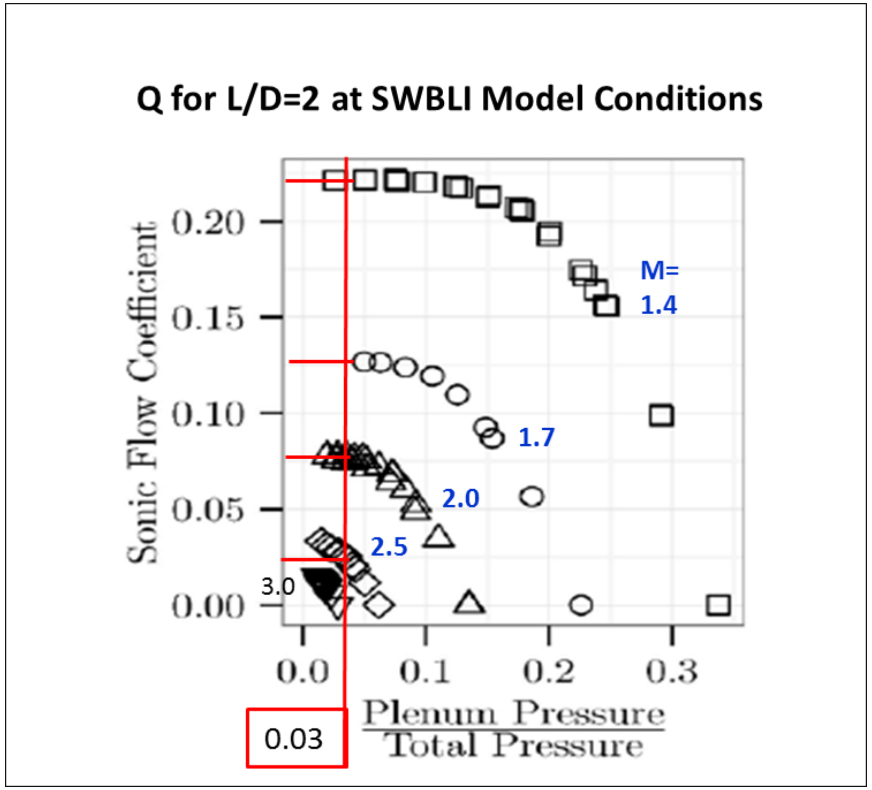


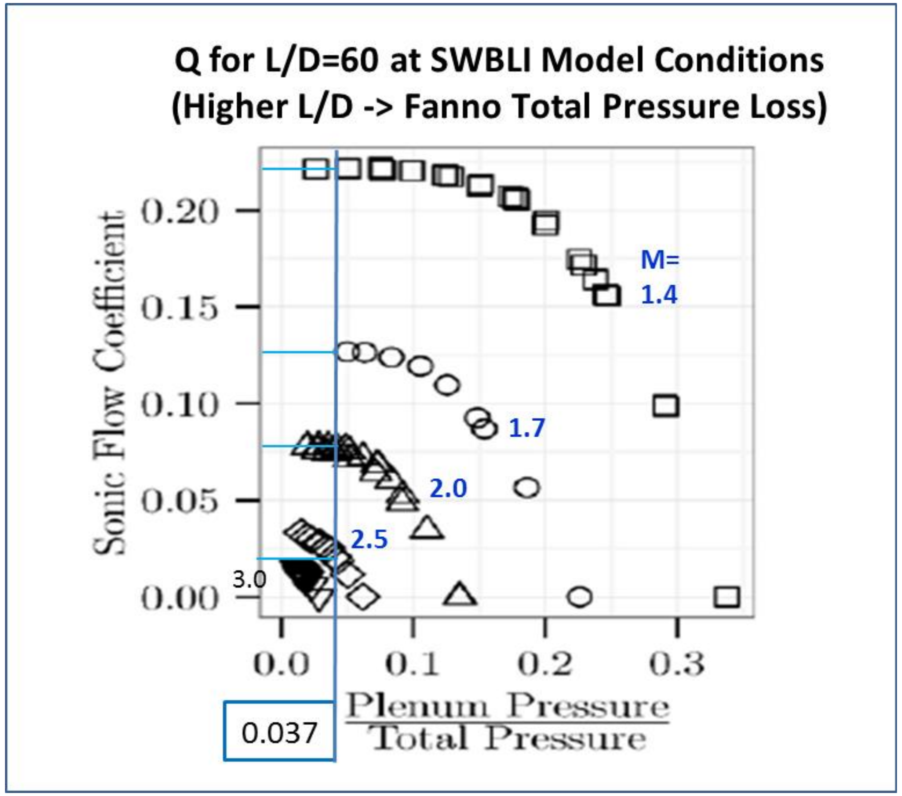




zone	Zone/Freestrm Mach=M_inf	Zone/Freestrm P_tot	Zone/Freestrm P_stat	Zone/Freestrm T_tot	Zone/Freestrm T_stat	Zone/Freestrm Sound Spd	Zone rho_stat	Zone rho_tot	Zone/Freestrm P_stat/P_tot
		(Pa)	(Pa)	(K)	(K)	(m/s)	(kg/m3)	(kg/m3)	(---)
0	3	143640.78	3910.43	302.59	108.07	208.40	0.126	1.654	0.027
1	2.47	137277.49	8418.62	302.59	136.29	234.04	0.215	1.580	0.061
2	2.045	133722.00	15933.58	302.59	164.78	257.33	0.337	1.539	0.119
3	1.669	131368.50	27885.06	302.59	194.33	279.46	0.500	1.512	0.212
4	1.3	129542.47	46753.68	302.59	226.15	301.47	0.720	1.491	0.361

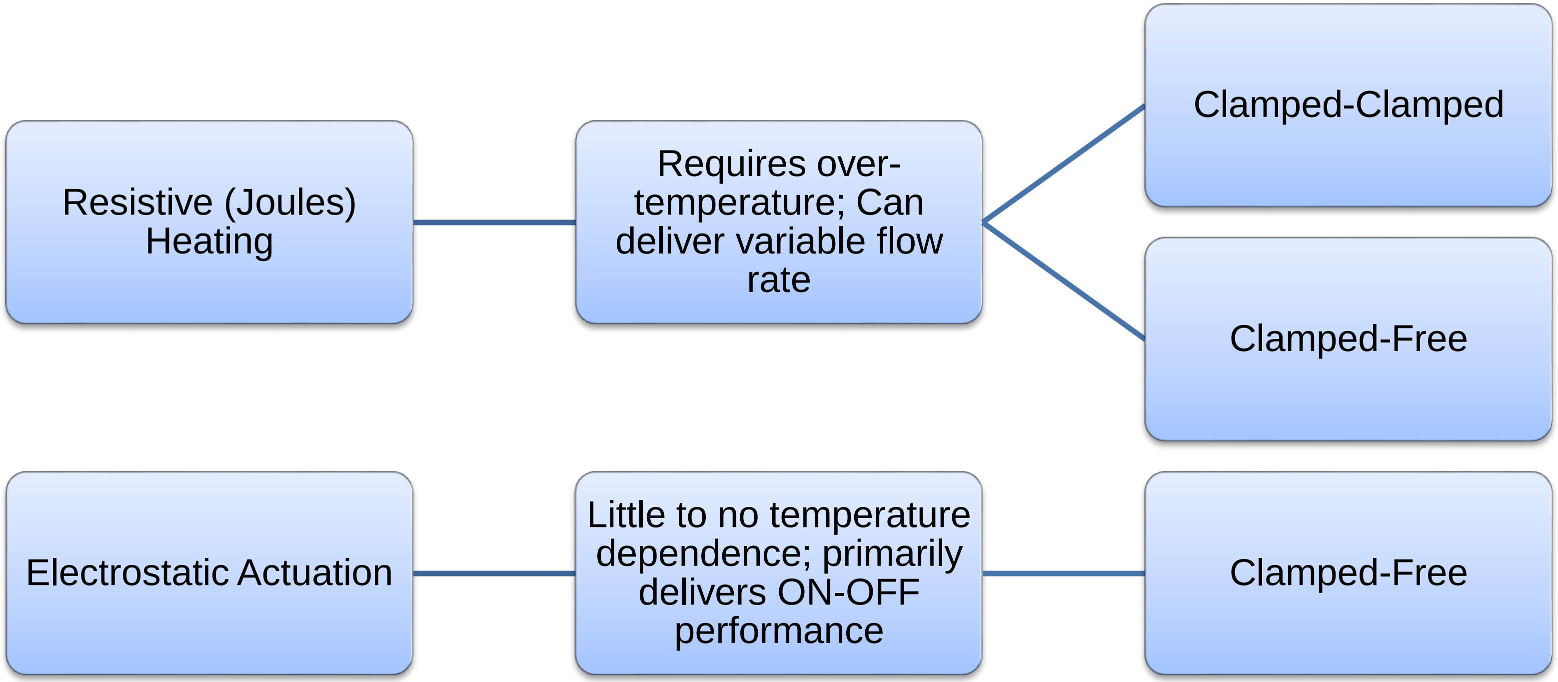
Calculated Q reduction for L/D=60 Bleed Channel
(at SWBLI Model Conditions)

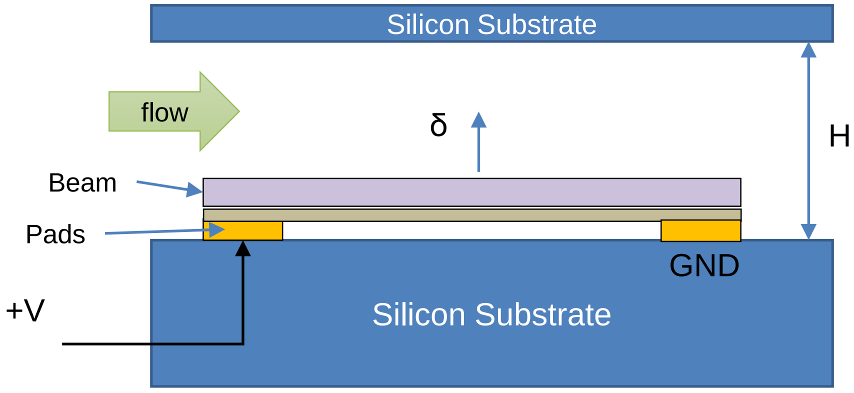




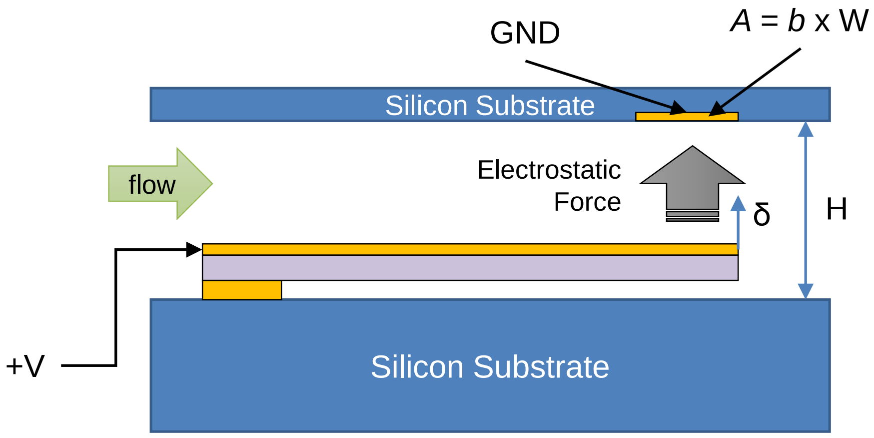
M=1.4-2.0, bleed hole entrance is choked: No Q Reduction
M=2.5, bleed hole entrance is not choked: 10-20% Q Reduction
(Data from NASA/TM-2013-217843)

Control Valve Trade Space





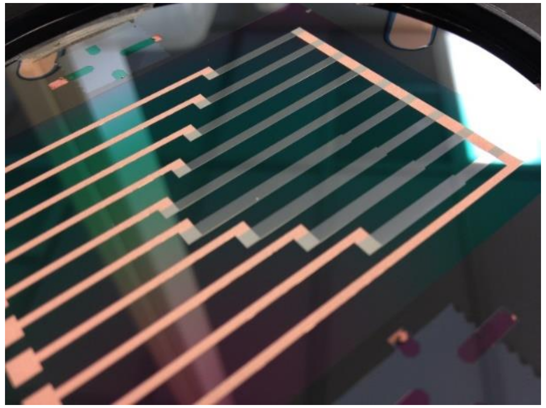
Resistive (clamped-clamped)

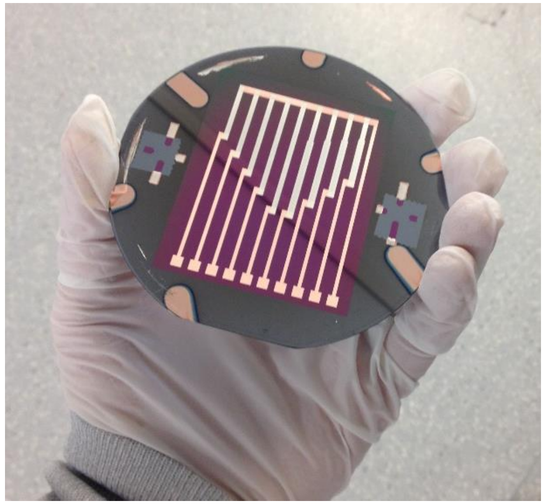


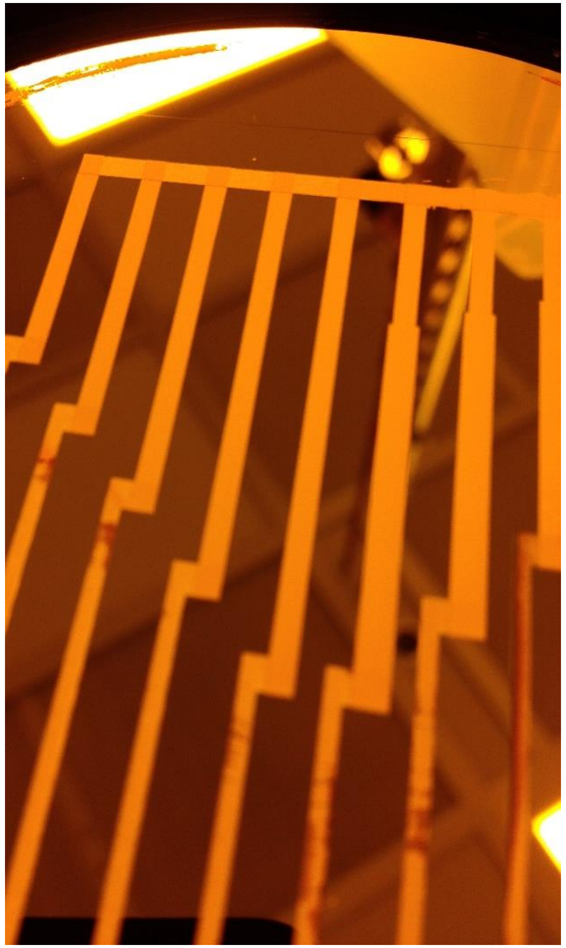
Electrostatic (clamped-free)

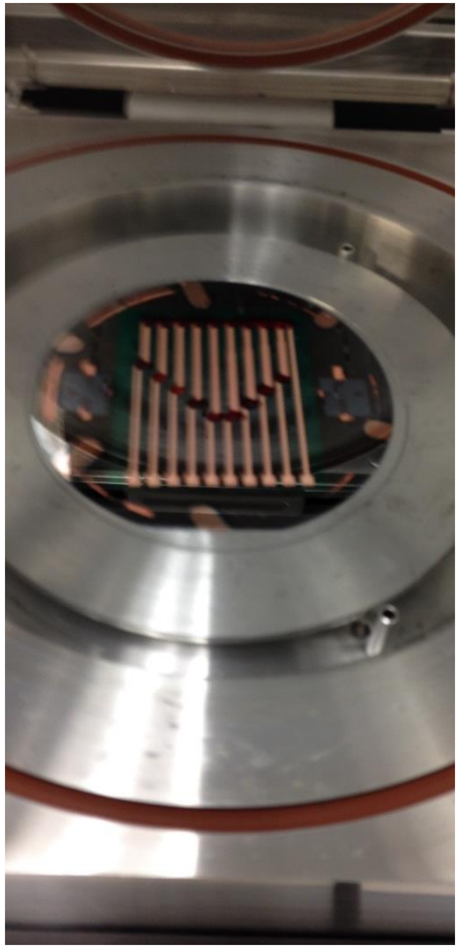
Control Valve – MEMS Fabrication

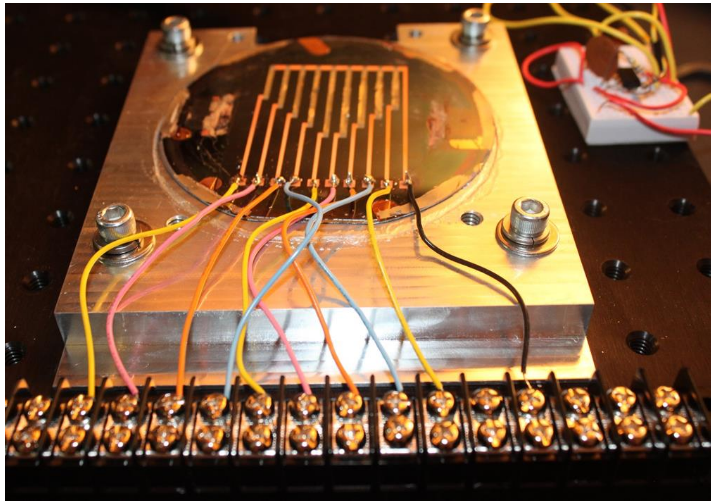
MEMS fabrication of relevant clamped-clamped beam structures was done to demonstrate flow regulation under relevant conditions

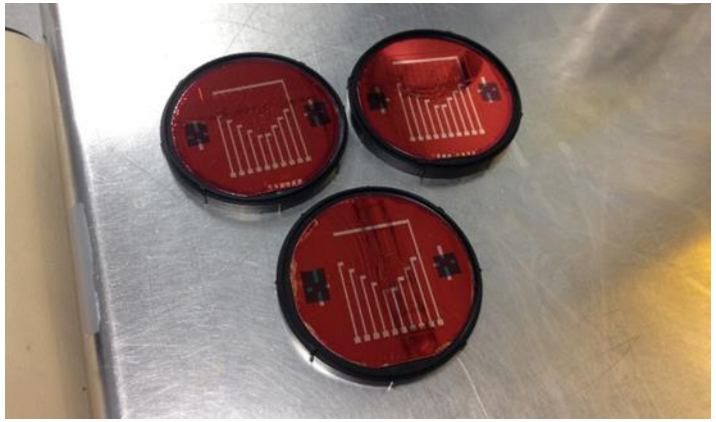




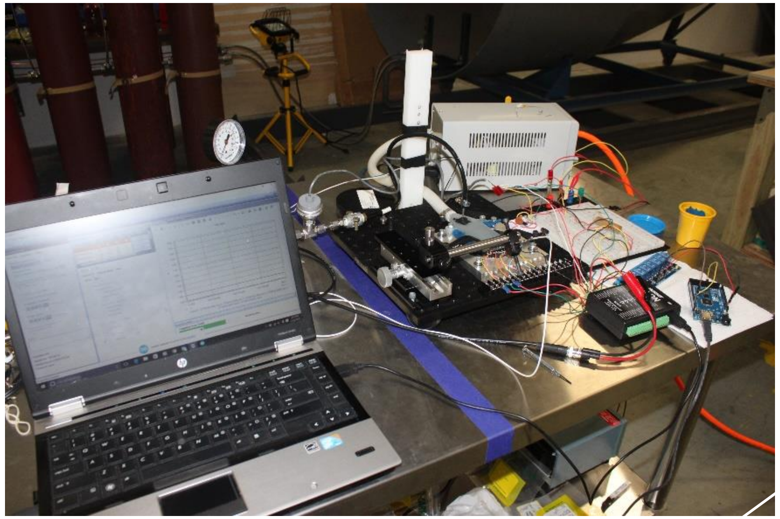


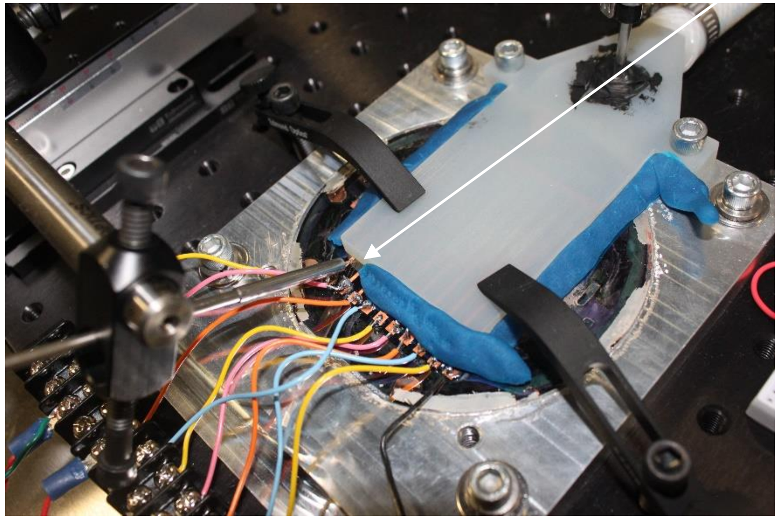


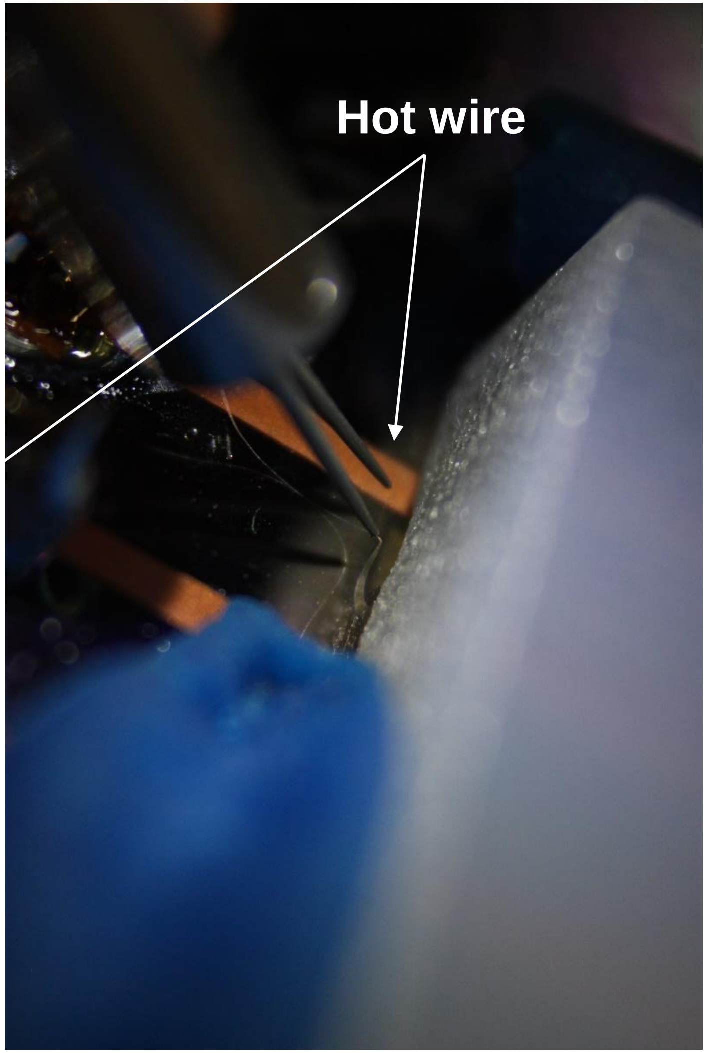




Setup for Risk Reduction Testing



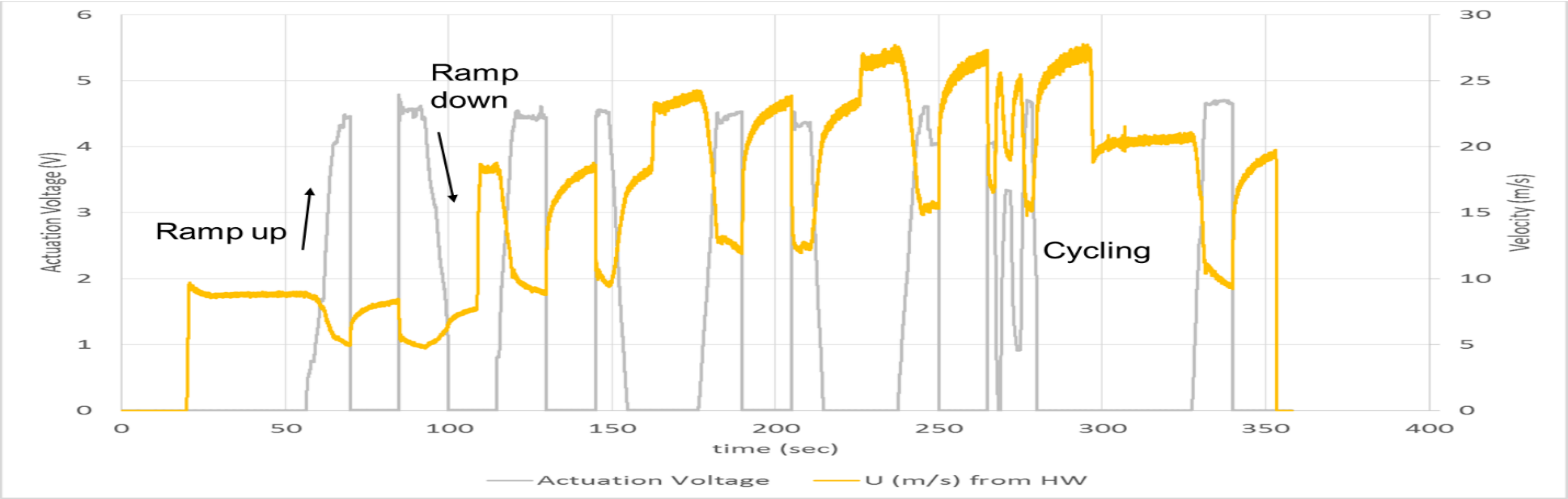




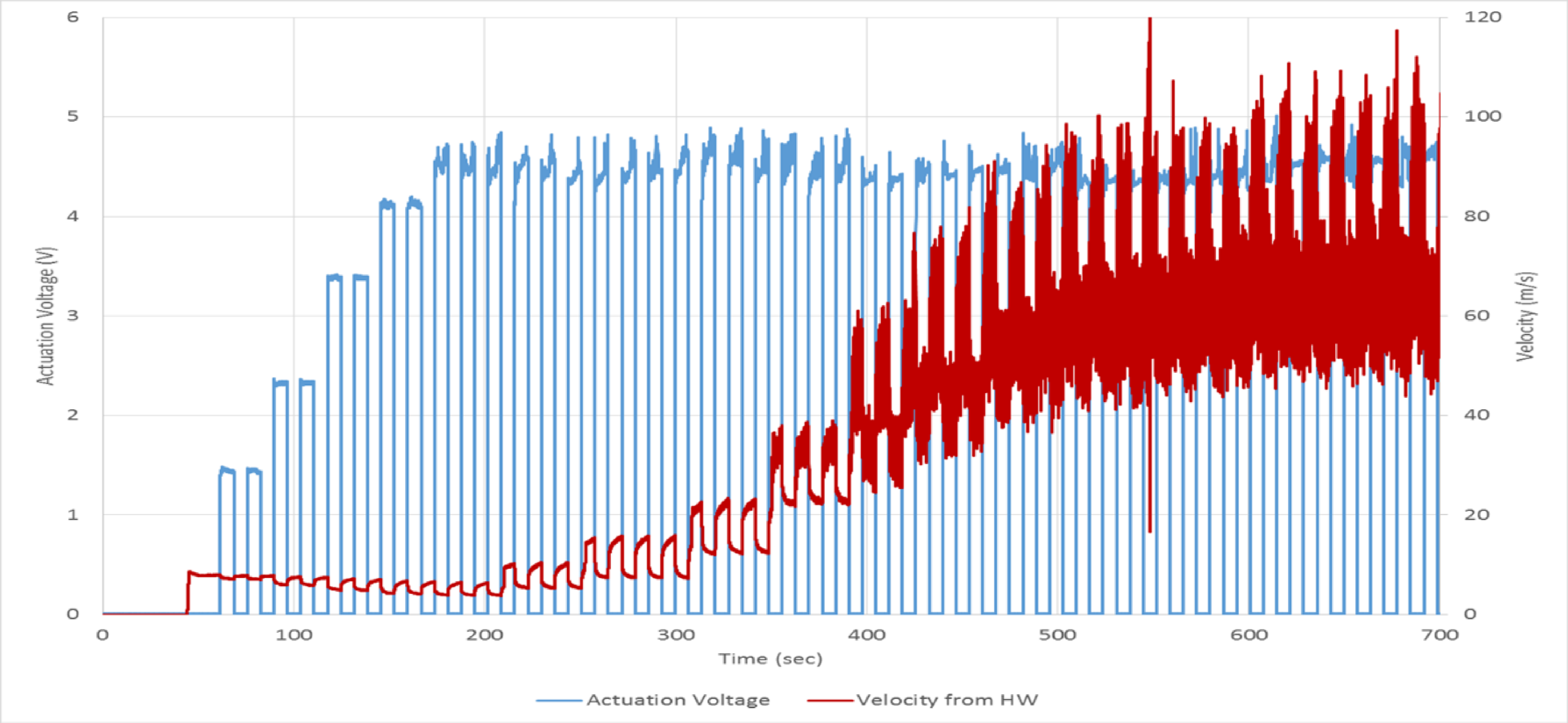
Results from Risk Reduction Testing

Testing of micro-valve structure

- Static testing – demonstrate valve actuation under an applied voltage
- Dynamic testing – demonstrate valve actuation within channel and under relevant fluid flow conditions.
- Perform additional testing: response, cycling, pressure loading and sealing



Flow Regulation



Metrics Summary

Metric Identifier	Threshold	Objective	Estimated	Achieved (Phase I)	Supporting Arguments
Pressure Differential	6.78 psi	11 psi (0.75 atm)	> 6.78 psi	1.8 psi (NOTE: in the absence of significant losses at the entry point, this pressure differential was not truly indicative of SWBLI model conditions)	During the risk reduction testing a bulk velocity of more than 100 m/s was handled by the control valve structure. This is close to what is expected under Zone 4 conditions.
Discharge Coefficient	0.74	0.74	0.74	--	Based on analysis, the µPBI unit as preliminarily designed should meet the discharge coefficient metric for all zones, except for zone 2 where perhaps a 20% mass flow deficit may be incurred.
Bleed Zone Porosity	25%	40%	> 25 %	31%	A cover plate configuration was designed and manufactured to yield a porosity higher than threshold.
Total Temperature	90 °F	500 °F	500 °F	70 °F	Risk reduction testing of the control valve was done at room temperature conditions; Materials of construction have a viable path to meeting threshold, and even objective. Operating at the latter will require modifications to the operating principles and/or MEMS fabrication process.
Turn Time	< 24 hrs	Identify Limit	~O(s)	~O(s)	The response of the control valve and ability to regulate flow quickly was demonstrated during the risk reduction testing.

Test Results Summary / Conclusions

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- During the Phase I effort, a novel solution to parametric inlet bleed testing was developed and key component technologies were demonstrated as part of bench scale risk reduction testing
- The construction of the µPBI module leveraged MEMS design and fabrication processes that enable to batch produce small mechanical structures (serving as control valves) embedded in micro-fluidic passages, along with electrical pathways and sensing elements, all integrated together on silicon wafers.
- The risk reduction fabrication and testing performed during the Phase I effort focused primarily on the mechanical structures serving as the control valve to regulate flow within the micro fluidic flow passage.
    - Static testing demonstrated actuation of valve structures with quick response
    - Dynamic testing demonstrated 50% flow velocity reduction
    - Maximum pressure differential operation demonstrated = 1.81 psi
        - Dynamic equivalent of greater than 100 m/s bulk flow velocity, close to what expected under Zone 4 conditions
        - Trend shows that threshold pressure differential could be met.
    - Tests demonstrate fine control of valve operation to regulate flow.
- The Phase I effort provide significant risk reduction regarding the initially proposed µPBI concept by demonstrating actuation of a MEMS fabricated valve structures under dynamic flow conditions of similar strength as those anticipated in the AFRL SWBLI model.

Acknowledgments

AFRL SBIR Phase 1 Project

Contract # FA8650-15-M-2616

USAF/AFMC/AFRL/RQH

HIGH-SPEED SYSTEMS DIVISION

AFRL WRIGHT RESEARCH SITE

2130 EIGHTH STREET, BUILDING 45

WRIGHT-PATTERSON AFB OH 45433-7541

Technical Monitor: Andrew H. Lloyd, 2D LT, USAF