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14. ABSTRACT
This work builds on our previous experimental studies of high-speed separated base flows by performing innovative passive and active flow-control experiments on these flowfields. The purpose of these studies is twofold: (1) to effect substantial changes in these base flows that will lead to improved flight vehicle performance; and (2) to further basic understanding of these complex, separated, compressible, turbulent flowfields. The specific passive-control studies that have been conducted consist of inserting splitter plates into the recirculation region to

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Report Title

Passive and Active Control of Massively Separated High-Speed Flows

ABSTRACT

This work builds on our previous experimental studies of high-speed separated base flows by performing innovative passive and active flow-control experiments on these flowfields. The purpose of these studies is twofold: (1) to effect substantial changes in these base flows that will lead to improved flight vehicle performance; and (2) to further basic understanding of these complex, separated, compressible, turbulent flowfields. The specific passive-control studies that have been conducted consist of inserting splitter plates into the recirculation region to alter the stability characteristics and structure of the near-wake flowfield. The open-loop active control methods that were employed used electric-arc excitation to force or inhibit specific instability modes for these high-speed separated flows. Two electric-arc actuator types were investigated: localized arc-filament plasma actuators and pulsed plasma-jet actuators. In each case, the studies were suggested by our previous experimental investigations that have characterized in detail the uncontrolled flowfields and also by recent DNS/stability studies of other workers. This final report summarizes our progress on both the passive splitter plate and active electric-arc control studies.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/12/2013	17.00	Todd M. Reedy, Nachiket V. Kale, J. Craig Dutton, Gregory S. Elliott. Experimental Characterization of a Pulsed Plasma Jet, AIAA Journal, (06 2013): 0. doi: 10.2514/1.J052022
07/29/2013	16.00	Bradley DeBlauw, Bradley Sanders, Nick Glumac, Craig Dutton, Gregory Elliott. Correlation Between Emission, Electric, and Flow Properties of Arc-Filament Plasma Actuators, AIAA Journal, (04 2013): 922. doi: 10.2514/1.J051853
08/03/2012	10.00	Todd M. Reedy, Gregory S. Elliott, J. Craig Dutton, Yeol Lee. Passive Control of High-Speed Separated Flows Using Splitter Plates, AIAA Journal, (07 2012): 1586. doi:

TOTAL: 3

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

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None since last progress report (8/31/2013).

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Received		Paper
02/01/2012	9.00	Bradley G. DeBlauw, Eli Lazar, Nachiket Kale, Nick Glumac, Craig Dutton, Gregory Elliott. Flow and Thermal Properties Induced by Electric Arc Plasma Actuators, 2011 AIAA Aerospace Sciences Meeting. 04-JAN-11, . : ,
07/12/2013	18.00	Bradley DeBlauw, Gregory Elliott, Craig Dutton. Active Control of Supersonic Base Flows with Electric Arc Plasma Actuators, 51st AIAA Aerospace Sciences Meeting. 07-JAN-13, . : ,
08/03/2012	11.00	Bradley Sanders, Nick Glumac, Craig Dutton, Gregory Elliott, Bradley DeBlauw. Correlation between Emission, Electric, and Flow Properties of Arc Filament Plasma Actuators, 2012 AIAA Aerospace Sciences Meeting. 09-JAN-12, . : ,
08/03/2012	13.00	Nachiket V. Kale, J. Craig Dutton, Gregory S. Elliott4, Todd M. Reedy. Experimental Characterization of a Pulsed Plasma Jet, 2012 AIAA Aerospace Sciences Meeting. 09-JAN-12, . : ,
08/03/2012	12.00	Bradley Sanders, Bradley DeBlauw, Gregory Elliott, Craig Dutton, Nick Glumac. Temporally and Spatially Resolved Spectroscopic Measurements of Plasma Actuator Thermal Properties, 2012 AIAA Aerospace Sciences Meeting. 09-JAN-12, . : ,
08/16/2011	5.00	Todd M. Reedy, Gregory S. Elliott, J. Craig Dutton, Yeol Lee. Passive Control of High-Speed Separated Flows Using Splitter Plates, 2011 AIAA Aerospace Sciences Meeting. 03-JAN-11, . : ,

TOTAL: **6**

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

(d) Manuscripts

Received		Paper
07/12/2013	19.00	Bradley DeBlauw, Gregory Elliott, Craig Dutton. Active Control of Supersonic Base Flows with Electric Arc Plasma Actuators, AIAA Journal (02 2013)
08/03/2012	14.00	Todd M. Reedy, Nachiket V. Kale, J. Craig Dutton, Gregory S. Elliott. Experimental Characterization of a Pulsed Plasma Jet, AIAA Journal (03 2012)
08/03/2012	15.00	Bradley Sanders, Bradley DeBlauw, Nick Glumac, Craig Dutton, Gregory Elliott. Correlation between Emission, Electric, and Flow Properties of Arc Filament Plasma Actuators, AIAA Journal (01 2012)
08/22/2011	8.00	T.M. Reedy, G.S. Elliott, J.C. Dutton, Y. Lee. Passive Control of High-Speed Separated Flows Using Splitter Plates, AIAA Journal (08 2011)
12/05/2013	22.00	Bradley DeBlauw, Gregory Elliott, Craig Dutton. Active Control of Supersonic Base Flows with Electric Arc Plasma Actuators, AIAA Journal (revision submitted) (10 2013)

TOTAL: **5**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

None

Patents Awarded

None

Awards

None since last progress report (8/31/2013).

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Todd Reedy	0.50	
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
None	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
J. Craig Dutton	0.04	
Gregory S. Elliott	0.04	
FTE Equivalent:	**0.08**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Richie Orozco	0.50	Aerospace Engineering
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Student Metrics

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

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME	
None	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Todd Reedy	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
None	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

PASSIVE AND ACTIVE CONTROL OF MASSIVELY SEPARATED HIGH-SPEED FLOWS

J. Craig Dutton Gregory S. Elliott
Department of Aerospace Engineering
University of Illinois at Urbana-Champaign

This work builds on our previous experimental studies of high-speed separated base flows by performing innovative passive and active flow-control experiments on these flow fields. The complete results of this research program are detailed in the two Ph.D. dissertations that are the primary intellectual products of the research performed: those of Bradley DeBlauw and Todd Reedy. These dissertations have been uploaded separately as part of the reporting process for this grant and need not be repeated here for sake of conciseness (over 400 pages total). However, the abstracts from these dissertations are presented below to establish the scope of the accomplishments and contributions made in this research effort. The dissertations may be consulted for complete details, in addition to the resulting conference and journal articles that have been are continuing to be published.

Active Control of Massively Separated High-Speed/Base Flows with Electric Arc Plasma Actuators

Bradley DeBlauw
Ph.D. Dissertation
September 2012

Abstract

The current project was undertaken to evaluate the effects of electric arc plasma actuators on high-speed separated flows. Two underlying goals motivated these experiments. The first goal was to provide a flow control technique that will result in enhanced flight performance for supersonic vehicles by altering the near-wake characteristics. The second goal was to gain a broader and more sophisticated understanding of these complex, supersonic, massively-separated, compressible, and turbulent flow fields. The attainment of the proposed objectives was facilitated through energy deposition from multiple electric-arc plasma discharges near the base corner separation point. The control authority of electric arc plasma actuators on

a supersonic axisymmetric base flow was evaluated for several actuator geometries, frequencies, forcing modes, duty cycles/on-times, and currents.

Initially, an electric arc plasma actuator power supply and control system were constructed to generate the arcs. Experiments were performed to evaluate the operational characteristics, electromagnetic emission, and fluidic effect of the actuators in quiescent ambient air. The maximum velocity induced by the arc when formed in a 5 mm x 1.6 mm x 2 mm deep cavity was about 40 m/s. During breakdown, the electromagnetic emission exhibited a rise and fall in intensity over a period of about 340 ns. After breakdown, the emission stabilized to a near-constant distribution. It was also observed that the plasma formed into two different modes: “high-voltage” and “low-voltage”. It is believed that the plasma may be switching between an arc discharge and a glow discharge for these different modes. The two types of plasma do not appear to cause substantial differences on the induced fluidic effects of the actuator. In general, the characterization study provided a greater fundamental understanding of the operation of the actuators, as well as data for computational model comparison.

Preliminary investigations of actuator geometry in the supersonic base flow determined that inclined cavity and normal cavity actuators positioned on the base near the base edge could produce significant disturbances in the shear layer. The disturbances were able to be tracked in time with phase-locked schlieren imaging and particle image velocimetry (PIV). The final set of flow control experiments were therefore performed with an eight-actuator base using the inclined cavity actuator geometry. The actuators were able to cause moderate influences on the axisymmetric shear layer velocity profile and base pressure. The most substantial changes to the shear layer and base pressure were noted for the highest current and duty cycle tests. At 1 A and 20% duty cycle, the base pressure was reduced by 3.5%. Similar changes were noted for all modes and a range of frequencies from about 10-30 kHz. Increases in duty cycle between 4% and 20% caused a nearly linear decrease in base pressure.

Analysis of the shear layer velocity profiles acquired through PIV show a local thickening of the shear layer in the region of the disturbances caused by the actuator. A slight increase in thickness was also observed away from the disturbance. Disturbances were able to be tracked at all frequencies and translated along the shear layer at a convective velocity of 430 ± 20 m/s. A fairly clear trend of increasing velocity disturbance amplitude correlating to increasing base pressure changes was noted. Moreover, the ability of the disturbances to stay well organized further down the shear layer also appears to be a significant factor in the actuators' effect on base pressure. Consistent with these observations, it appears that increased duty cycle causes increased shear layer disturbance amplitudes.

The use of PIV has enabled substantial insight to be gained into the effects of the actuators on the ensemble-averaged flow field and on the variability of the instantaneous flow field with and without control. A sensitive bimodal recirculation region behavior was found in the no-control flow field that the plasma actuators could force. The flow field and turbulence statistics in each mode were substantially different. Through analysis of past no-control base pressure measurements, it is believed that the bimodal behavior fluctuates at a characteristic frequency between 0.4 and 0.5 Hz [$St_D = O(5 \times 10^{-5})$]. The flat time-averaged base pressure distribution is due to the superposition of a normally non-flat instantaneous base pressure distribution. Also, the standard deviation of the base pressure measurements is reduced when in one recirculation region mode as compared to when it is fluctuating between recirculation region modes.

Control of Supersonic Axisymmetric Base Flows Using
Passive Splitter Plates and Pulsed Plasma Actuators

Todd Reedy

Ph.D. Dissertation
October 2013

Abstract

An experimental investigation evaluating the effects of flow control on the near-wake downstream of a blunt-based axisymmetric body in supersonic flow has been conducted. To better understand and control

the physical phenomena that govern these massively separated high-speed flows, this research examined both passive and active flow-control methodologies designed to alter the stability characteristics and structure of the near-wake. The passive control investigation consisted of inserting splitter plates into the recirculation region. The active control technique utilized energy deposition from multiple electric-arc plasma discharges placed around the base. The flow-control authority of both methodologies was evaluated with experimental diagnostics including particle image velocimetry, schlieren photography, surface flow visualization, pressure-sensitive paint, and discrete surface pressure measurements.

Using a blowdown-type wind tunnel reconstructed specifically for these studies, baseline axisymmetric experiments without control were conducted for a nominal approach Mach number of 2.5. In addition to traditional base pressure measurements, mean velocity and turbulence quantities were acquired using two-component, planar particle image velocimetry. As a result, substantial insight was gained regarding the time-averaged and instantaneous near-wake flow fields. This dataset will supplement the previous benchmark point-wise laser Doppler velocimetry data of Herrin and Dutton (1994) for comparison with new computational predictive techniques.

Next, experiments were conducted to study the effects of passive triangular splitter plates placed in the recirculation region behind a blunt-based axisymmetric body. By dividing the near-wake into 1/2, 1/3, and 1/4 cylindrical regions, the time-averaged base pressure distribution, time-series pressure fluctuations, and presumably the stability characteristics were altered. While the spatial base pressure distribution was influenced considerably, the area-integrated pressure was only slightly affected. Normalized RMS levels indicate that base pressure fluctuations were significantly reduced with the addition of the splitter plates. Power-spectral-density estimates revealed a spectral broadening of fluctuating energy for the 1/2 cylinder configuration and a bimodal distribution for the 1/3 and 1/4 cylinder configurations. It was concluded that the recirculation region is not the most sensitive location to apply flow control; rather, the shear layer may be a more influential site for implementing flow control methodologies.

For active flow control, pulsed plasma-driven fluidic actuators were investigated. Initially, the performance of two plasma actuator designs was characterized to determine their potential as supersonic flow control devices. For the first actuator considered, the pulsed plasma jet, electro-thermal heating from an electric discharge heats and pressurizes gas in a small cavity which is exhausted through a circular orifice forming a synthetic jet. Depending on the electrical energy addition, peak jet velocities ranged between 130 to nearly 500 m/s when exhausted to quiescent, ambient conditions. The second plasma actuator investigated is the localized arc filament plasma actuator (LAFPA), which created fluidic perturbations through the rapid, local thermal heating, generated from an electric arc discharge between two electrodes within a shallow open cavity. Electrical and emission properties of the LAFPA were first documented as a function of pressure in a quiescent, no-flow environment. Rotational and vibrational temperatures from N_2 spectra were obtained for select plasma conditions and ambient pressures. Results further validate that the assumption of optically thin conditions for these electric arc plasmas is not necessarily valid, even at low ambient pressure. Breakdown voltage, sustained plasma voltage, power, and energy per pulse were demonstrated to decrease with decreasing pressure.

Implementing an array of eight electric arcs circumferentially around the base near the corner expansion, the LAFPA actuators were shown to produce significant disturbances to the separating shear layer of the base flow and cause modest influences on the base pressure when actuated over a range of high frequencies (*O*(kHz)), forcing modes, duty cycles, and electrical currents. To tailor the plasma actuator toward the specific flow control application of the separated base flow, several actuator geometries and energy additions were evaluated. Displaying the ability to produce disturbances in the shear layer, an open cavity actuator design outperformed the other geometries consisting of a confined cavity with an exhaust orifice. Increases in duty cycle (between 2% and 6%) and in plasma current (1/4 to 4 amps) were shown to produce large velocity disturbances causing a decrease in average base pressure. At 4 amps and a maximum duty cycle of 6%, the largest measured change in area-weighted base pressure, near -1.5%, was observed for the axisymmetric forcing mode. Positive changes in base pressure were experienced (as much as 1% increase from the no-control) for the vertical and horizontal flapping modes.