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6. AUTHORS
Jesse Little

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Arizona
P.O. Box 210158, Rm 510

Tucson, AZ 85721 -0158

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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

TOTAL:

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:

(c) Presentations

Number of Presentations: 0.00

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

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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	National Academy Member
Jesse Little	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

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
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
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

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

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Scientific Progress

Equipment grant

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF ARIZONA
888 N EUCLID AVE
TUCSON AZ 85719-4824

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Final Report

A System for Highly Resolved Measurements of the Interaction of 3D Unsteady Flows with Aerodynamic Surfaces (66867-EG-RIP)

Army Research Office
Contract Number: W911NF-15-1-0355
Program Manager: Dr. Matthew Munson

Jesse Little
Associate Professor
Department of Aerospace and Mechanical Engineering
University of Arizona

March 2017

Table of Contents

1 Abstract

This report describes the purchase, installation and intended use of equipment comprising a system for highly resolved measurements of the interaction of 3D unsteady flows with aerodynamic surfaces. The purchase is composed of microphones, pressure scanners, high bandwidth pressure transducers, signal conditioner-amplifiers, filters, pressure sensitive paint (PSP) and components necessary to assemble two independent stereoscopic or one complete tomographic particle image velocimetry (PIV) system. The instrumentation is primarily intended to support research into the production, analysis and control of vortex-body interactions. This augments an ongoing ARO-funded project (W911NF-14-1-0662) aimed at harnessing the unique capabilities of active flow control (AFC) for unsteady aerodynamics research. The requested instrumentation is essential for quantifying the flow physics associated with unsteady 3D vortex body interactions and even nominally 2D cases which may develop local 3D features. This also enhances experimental capabilities that can be leveraged for other DoD projects currently funded by AFOSR, ONR and DoD contractors.

2 Introduction

The equipment consists of seven main components which together comprise a system for highly-resolved measurements of the interaction of unsteady 3D flows with aerodynamic surfaces. The total expenditures for the system were $244,705 ($88 over budget). The main components of the acquired system are tabulated below showing the budgeted and final costs. A brief description for each component including justification for major cost or vendor changes is included in Section 3.

Table 1: Summary of budgeted and purchased equipment.

Equipment	Supplier	Budgeted	Spent
Pressure Sensitive Paint System	ISSI	$ 58,000.00	$ 37,615.00
PIV Flowmaster System Upgrade	Lavision, etc	$ 138,920.00	$ 137,964.00
High Bandwidth Pressure Measurement Kit	Kulite	$ 8,755.00	$ 5,131.58
Signal Conditioner-Amplifier System	Ectron and Kemo	$ 7,035.00	$ 8,749.00
Miniature Pressure Scanners	Scanivalve	$ 19,780.00	$ 46,247.00
Microphone System	Bruel and Kjar	$ 12,127.00	$ 6,794.00
Hot wire anemometers	Dantec	n/a	$ 2,205.00
	Total	**$ 244,617.00**	**$ 244,705.58**
		Difference	**$ (88.58)**

This acquisition greatly enhances both research and research-related education capabilities of the Turbulence and Flow Control Laboratory (TFCL) at the University of Arizona directed by Prof. Jesse Little. The replacement value of the equipment and experimental facilities used by the TFCL and its collaborators is well-over several million dollars. The TFCL currently employs 2 post-docs, 4 PhD students, 4 MS students and 7 BS students working on various DoD-related projects. A newly established program with TU Berlin has resulted in a steady stream (1-2 per year) of visiting students since 2013 with more scheduled through 2017. These students perform thesis research at the TFCL on various aspects of DoD-related projects. The acquisition of the requested equipment will also assist in research and research-related education of several other graduate students, postdoctoral researchers and research staff members working collaboratively with the TFCL.

The instrumentation is primarily intended for use in a relatively new (installed in Summer 2013) multipurpose closed-loop subsonic wind tunnel facility in the Department of Aerospace and

Mechanical Engineering (AME) at the University of Arizona. The wind tunnel, with 3ft x 4ft x 12ft test section, has a maximum velocity of 80m/s (*Re*=1.5M/ft) with mean flow uniformity better than 0.5%. Temperature is maintained within 1° F of ambient using a heat exchanger with chilled water supply. Turbulence intensity in the 5-80m/s velocity range is less than 0.12% from DC-10 kHz and less than 0.045% from 1Hz-10kHz with some speeds considerably lower. The tunnel also includes a 2D traverse and provisions for installation of various unsteadiness generators. The wind tunnel and instrumentation provides a truly unique capability to study 3D unsteady flows at Reynolds numbers commensurate with practical applications such as rotorcraft, turbomachinery and fixed wing flight in unsteady environments.

A sample flow field acquired during an existing ARO grant is provided in Figure 1 showing unsteadiness produced by ns-DBD plasma actuation at the airfoil leading edge. While the acquired instrumentation can be used for studying the flow over the airfoil shown, its primary intent is to investigate the interaction of this unsteadiness with an aerodynamic body placed in the wake. In addition, these items will enhance the quality and capabilities of both current and future research efforts related to ARO and general DoD areas of interest.

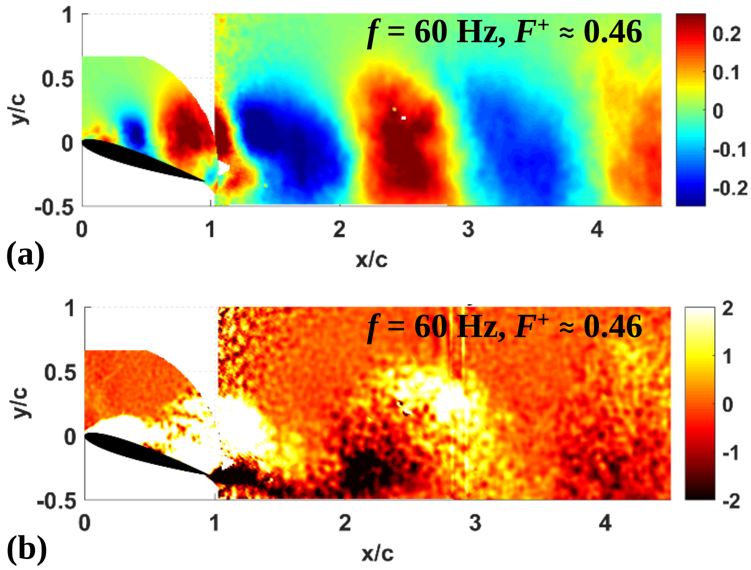

Figure 1. Sample phase-averaged PIV for ns-DBD plasma forcing at $F^+ \approx 0.46$ ($f_f = 60$ Hz) (a) Dimensionless Vertical Fluctuating Velocity (b) Dimensionless Spanwise Vorticity. Re=740,000 (U=40m/s) (Ashcraft et al. 2016).

3 Equipment Description

3.1 Pressure Sensitive Paint (PSP) System

PSP is an optical technique for measuring surface pressure based on oxygen modulation of emitted light (Gregory et al. 2014). PSP enables quantitative measurements with high spatial resolution in situations that are often too challenging for traditional pressure measurement techniques (e.g. large complicated surfaces and thin/sharp regions of models). This is essential for the study of 3D flow interactions with aerodynamic surfaces since it is unfeasible to fully instrument models with pressure taps. PSP is a relatively new diagnostic that is rapidly gaining popularity among experimental aerodynamicists.

The PSP system was purchased from ISSI, a recognized leader in PSP technology, at a total cost of $37,615. The acquisition consists of two cameras, air-cooled LED lamps, a delay generator, optics, paint, computer and software. The frequency response of PSP is primarily dependent on paint composition. The system purchased here is capable of fast response (up 20 kHz paint depending), but is sampled using a "slow" camera. This is partly chosen to reduce cost, but also maintains similar data acquisition techniques as the PIV system described in item 3.2 below. A pending ARO research instrumentation grant aims to extend this to a high-speed PSP.

The system has been installed for use in subsonic wind tunnel testing and has been successfully employed for velocities as low as 30 m/s. Figure 2 shows sample PSP data for AFC applied to the deflected flap of a trapezoidal wing which was chosen as a test case for shakedown of the system. As outlined above, the PSP system is intended for use in studies of vortex-body interactions which are Army-relevant due to their regular occurrence in rotorcraft and turbomachinery.

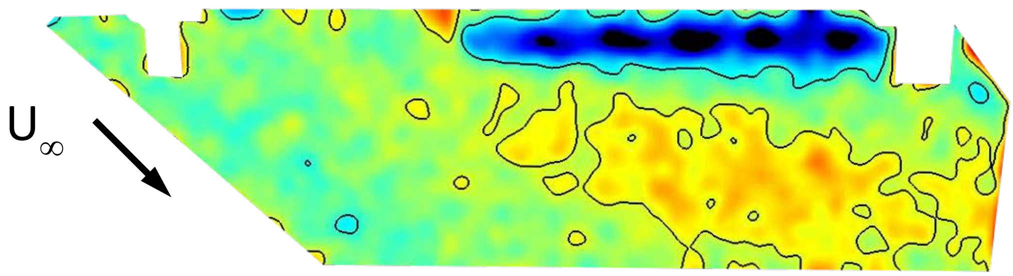

Figure 2: Sample PSP data for AFC applied to the flap of a generic trapezoidal wing (Rontsch et al. 2016). The image shows the difference between baseline and controlled flow and is used as an example to show the PSP capability which will be applied to the experiment referenced in Figure 1. The dark blue region represents an area were normally separated flow has been attached to the model resulting in a significant suction peak. Re=1,700,000 (U=30m/s), α=0°, δ=65°, C_μ=2%.

3.2 Particle Image Velocimetry (PIV) System Upgrade

PIV is a widely used technique for measuring quantitative velocity fields with high spatial resolution. PIV can provide 2D (single camera) and 3D stereoscopic (two camera) velocity fields along a plane. More recently, tomographic PIV (typically requiring 4 cameras) has been developed to acquire velocity measurements in a fluid volume (Elsinga et al. 2006). The main advantage of this method is the ability to determine velocity vectors and the velocity gradient tensor in a 3D measurement domain. Note that the Reynolds stress tensor is also provided for incompressible flows in both 3D stereoscopic and tomographic PIV. Tomographic PIV eliminates the ambiguity associated with planar techniques in highly 3D flows and offers numerous possibilities for implementing vortex identification schemes and analyzing flow structure/modes using, for example, proper orthogonal decomposition (POD) and its many relatives. Tomographic PIV has been validated using the vorticity equation and has also been used to calculate the spatial distribution of pressure via the Navier-Stokes equations (Scarano 2013).

A PIV system upgrade was purchased at a total cost of $137,964. The acquisition consists of a high energy laser, sCMOS camera and various opto-mechanical accessories. These components augment an existing system to allow either a single, four camera tomographic PIV setup or two independent stereoscopic PIV setups. The high energy laser (380 mJ/pulse @ 532nm and 10Hz) is essential for the large fields of view typically considered in the AME subsonic wind tunnel. PIV is a major workhorse in the TFCL and the system has already been integrated into regular use for an existing ARO grant. Figure 2 shows sample results for 2D PIV incorporating the new hardware. This research effort will be moving to a four camera tomographic setup in the future targeting the vortex-body interaction experiments described in reference to Figure 1.

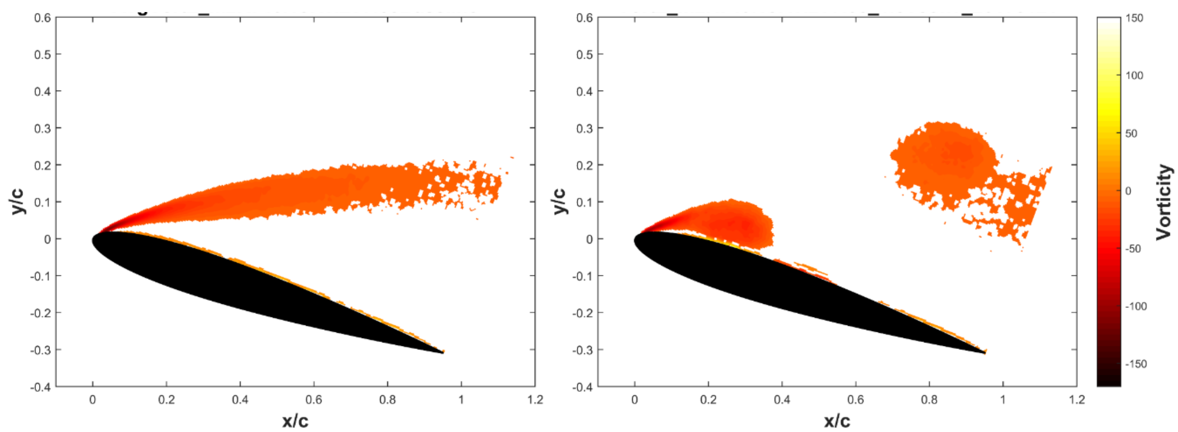

Figure 3: Sample phase-averaged PIV data for baseline and ns-DBD controlled flow using a single actuation pulse. Re=740,000 (U=40m/s).

3.3 High Bandwidth Pressure Measurement Kit

High bandwidth pressure sensors temporally resolve surface pressure fluctuations in unsteady flows. This provides time-resolved pressure data at select locations on aerodynamic surfaces. The time-resolved data complements spatially resolved measurements (PSP and PIV) described in items 3.1 and 3.2. In the PSP case, it also serves as a calibration/reference ensuring frequency response is sufficient in phase-locked operation. Simultaneous acquisition of temporally and spatially resolved data is essential for understanding the physics of 3D unsteady flow interactions. This also allows execution of data analysis techniques such as Fourier transforms, pressure-velocity correlations, stochastic estimation, and dynamic mode decomposition (DMD), etc.

The original proposal requested ten additional high bandwidth pressure sensors (Endevco model 8507C) to augment an existing supply bringing the total to 17. The intent was to construct a surface array that provides information on 3D aspects of the time-dependent flow-surface interaction. After the proposal was awarded, it was found that a departmental colleague and collaborator (I. Wygnanski) was in possession of over 20 of these units seeing little to no use. Since an excess of these units existed, the original intent was easily satisfied and it was therefore decided to invest in a slightly different system.

The purchased system is comprised of a specialized high bandwidth signal conditioner and two small diameter (0.062in) ultraminiature thin profile pressure sensors. The system was purchased from Kulite at a total cost of $5,131.58. Kulite is a recognized leader in pressure transducer technology and the main competitor to Endevco. These two companies are the main suppliers of this technology for subsonic wind tunnel testing. Note that Kulite's product line has more widespread options for pressure range and sensor size including the low profile sensors purchased here. These can be installed, for example, very near an airfoil leading edge whereas the Endevco models must be placed some distance downstream. The signal conditioner is a relatively new product item and has been introduced in response to requests from many researchers to more properly condition/characterize the frequency response of pressure sensors (Hurst et al. 2015). It is a two channel system which is appropriate for powering the two purchased units. However, it is also intended to provide a reference standard for signals produced by larger channel count amplifiers (see section 3.4) which are not designed specifically for use with high bandwidth pressure sensors in aerodynamic applications. The low profile sensors purchased here along with the larger-scale sensors already in the possession of the TFCL will be integrated into an airfoil that is to be placed in the unsteady wake as discussed in reference to Figure 1.

3.4 Signal Conditioner-Amplifier System

The signal conditioner-amplifier system is used for powering high bandwidth pressure sensors, accelerometers, strain gauges, etc. The units proposed here enable a wide variety of conditioning options (selectable gain, filter, etc). The original proposal requested seven additional channels to bring the total count to 22. This requirement was adjusted considering the availability of other systems in the department (e.g. section 3.3) and additional experience with signal conditioning requirements. Specifically, the filtering capability of the signal conditioning units was found to be a limiting factor in some situations relevant to the existing ARO work. It was therefore decided to increase the existing signal conditioning amplifier capacity to only 16 channels while adding more flexibility for filtering. The end result was a purchase of one additional signal conditioner channel from Ectron Corporation along with a bank of seven dedicated filters from Kemo, Inc. The total cost of this purchase was $8,749. Considering existing TFCL hardware, this now enables acquisition and filtering of 16 channels which also matches with the size of most data acquisition boards. This system directly supports the equipment discussed in section 3.3.

3.5 Miniature Pressure Scanners

Scanners are used for measuring large arrays of static pressure tap data at reduced cost compared to the high bandwidth sensors described in section 3.3. The scan rate of modern units is typically quite high (tens of kHz), but the length of tubing determines the frequency response of the actual measurement. Miniaturized pressure scanners that can be placed inside wind tunnel models minimize tube length allowing a cheaper alternative to expensive arrays of high bandwidth pressure transducers (e.g. section 3.3). The original proposal requested the purchase of two 32 channel miniaturized pressure scanners from Scanivalve Corporation. These scanners are small enough to fit inside wind tunnel models thus minimizing tube length and maximizing temporal resolution. Considering the size of the typical models in the AME subsonic wind tunnel (~1 ft chord) and additional hardware in the department (see section 3.3), it was decided to reduce to one 32 channel unit and augment with an additional larger 64 channel unit at a reduced pressure range. The frequency response of the installed miniaturized system is expected to be better than 100 Hz and, given the available hardware, it is possible to correct the 64 channel unit to similar values. This frequency response is sufficient for unsteady flows planned for ARO-relevant investigations (e.g. Figure 1) and it is also required for calibration/reference of the PSP system described in section 3.1. Both units interface with an existing system in the TFCL expanding the total available channel count to 256. A miscommunication between the PI and Scanivalve during the original proposal budget resulting in an underestimate of the required cost as the necessary A/D convertors were excluded. Thus, the original proposed budget for this item was unreasonably low and actual expenditures ($46,247) were significantly higher than estimated. However, this was absorbed by acquisition of some other items at lower cost than estimated in the original budget.

3.6 Microphone System

A four channel microphone system was requested for quantifying the acoustic field in the unsteady experiments. Microphones measure the unsteady flow field produced by AFC as well as the acoustic signature of its interaction with a downstream aerodynamic surface (e.g. airfoil). A microphone system is required to separate the acoustic fluctuations from velocity fluctuations measured by an existing constant temperature anemometry system. The original proposal requested purchase of the entire four channel microphone system. It was later found that a departmental colleague and collaborator (I. Wygnanski) was in possession of a four channel unit in need of recalibration and repair along with two microphones. The device in question had been lightly used and there were no plans for resuscitating it in the near future. As part of this award, the unit was repaired and recalibrated at a much cheaper cost than buying a new model. Also, required number of microphones for purchase were reduced to only two. Thus, the final cost of this item was only $6,794.

3.7 Constant Temperature Anemometry

The sum of the originally requested equipment (with modifications as discussed in previous sections) was approximately $2,000 under budget. Consequently, these funds were used to augment an existing constant temperature anemometry system from Dantec Dynamics. This system has been used heavily during the existing ARO grant and required repair of some broken components (hot wires) as is often the case in these experiments. The total cost of the repaired wires was $2,205. Figure 4 shows a sample of data taken using this equipment for the existing ARO grant. The wake characterization performed here sets the stage for introduction of an airfoil model to the unsteady wake during which the full potential of the DURIP award will be realized. Presently, the construction of a second airfoil model is nearing completion with experiments to commence in the next weeks.

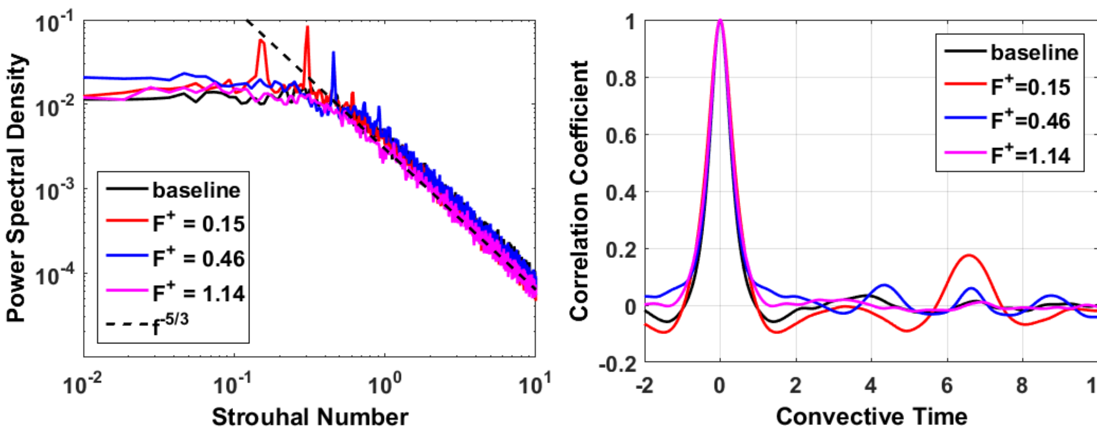

Figure 4: Power spectral density (PSD) and autocorrelations acquired at x/c=7 for ns-DBD plasma forcing along the leading edge of a NACA 0012 airfoil at various frequencies (Ashcraft, et al. 2016). Re=740,000 (U=40m/s).

3.8 Estimated useful life of the equipment

The estimated useful life of the PSP system and PIV system upgrade (both laser and camera) is 10-15 years. The estimated life of the pressure scanners, microphone system, signal conditioner-amplifiers and filters is 15-20 years. The estimated life of the high bandwidth pressure sensor and hot-wire anemometers is 5-10 years.

4 Summary

The research and research-related education capabilities of the TFCL and AME Department in general have been substantially enhanced by this DURIP award. Previously, there were no PSP systems at the University of Arizona, which was unfortunate given the substantial amount of ongoing aerodynamics related-research both in the PIs lab and other research groups. The higher energy laser (380 mJ) has nearly doubled previous capabilities (200 mJ) enabling examination of larger flow fields. This is crucial for measurements in the 3ft x 4ft x 12ft AME subsonic wind tunnel. The additional PIV camera permits the assembly of a four camera tomographic system and eliminates requirements for sharing hardware among various groups. This is particularly important for tomographic PIV since the setup is intensive. Acquisition of the camera and laser also allows assembly of two independent stereoscopic PIV systems and this capability has already been leveraged. Independent stereoscopic systems are essential since portions of the existing PIV hardware are shared among 4 faculty. The addition of pressure scanners increases increase our channel count to 256. The small footprint of the miniature scanner allows placement inside models for improved frequency response and calibration of other units in unsteady flow environments. The high bandwidth pressure transducers, signal conditioner-amplifiers and filters provide capacity for up to 16 channels of simultaneous measurements. This is exceptional for quantifying 3D unsteady flow interactions since it allows the creation of an array of sensors along the airfoil model including near the leading edge. The microphone system provides much needed capability for measuring the acoustic field in various wind tunnel experiments and specifically those produced in the ARO efforts.

The acquisition of this instrumentation provides a truly unique set of measurement capabilities in academia. When coupled with existing hardware, one can envision an experiment in which *simultaneous* measurements of tomographic PIV, spatially-resolved surface pressure (via PSP), high bandwidth surface pressure, constant temperature anemometry, acoustic fields (via microphones) and force data (via a 5 component balance) are acquired. This truly exceptional capability provides the potential for unprecedented insight into the nature of 3D unsteady flow interactions. It also fosters even closer collaboration with computational fluid dynamics research groups, both at the University of Arizona and the aerospace community at large, since similar data analysis procedures can be performed on both types of high resolution data sets. Finally, the availability of this instrumentation improves capability for training both graduate and undergraduate students in courses and funded research projects. This will be executed in part by introducing concepts and demonstrations in existing undergraduate and future graduate level courses taught by the PI. Graduate level courses will not only target experimentalists, but also students performing research in computational/theoretical areas both inside and outside of traditional fluids. In this way, collaborative thinking is fostered early in the educational development of graduate students.

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