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1. REPORT DATE (DD-MM-YYYY) 02-01-2015		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Sep-2013 - 31-Aug-2014	
4. TITLE AND SUBTITLE Final Report: Transonic Wind Tunnel Modernization for Experimental Investigation of Dynamic Stall in a Wide Range of Mach Numbers by Plasma Actuators with Combined Energy/Momentum Action			5a. CONTRACT NUMBER W911NF-13-1-0328		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611103		
6. AUTHORS Richard Miles, Andrey Starikovskiy			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Princeton University PO Box 36 87 Prospect Avenue, Second Floor Princeton, NJ 08544 -2020			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 63477-EG-RIP.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This equipment grant supported the design and construction of a subsonic variable speed wind tunnel for the study of plasma based methods for the control of dynamic stall for helicopter rotor blades. The tunnel has a 3D positioning system and servomotor mounted below the test section connected to the model through a 6-component transducer. This control system allows complete synchronization of all events: dynamic pitching frequency and pitching angle, free stream speed, actuator's timing, and all 6-component forces measurements. The wind tunnel is fitted with large windows for extended optical access to permit various non-intrusive and minimally-intrusive					
15. SUBJECT TERMS Variable Geometry Wind Tunnel, Low Turbulence, Dynamic Stall, Plasma Actuators, Femtosecond laser tagging					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT			c. THIS PAGE	Richard Miles
UU	UU	UU	UU	19b. TELEPHONE NUMBER	
			609-258-5131		



## Report Title

Final Report: Transonic Wind Tunnel Modernization for Experimental Investigation of Dynamic Stall in a Wide Range of Mach Numbers by Plasma Actuators with Combined Energy/Momentum Action

### ABSTRACT

This equipment grant supported the design and construction of a subsonic variable speed wind tunnel for the study of plasma based methods for the control of dynamic stall for helicopter rotor blades. The tunnel has a 3D positioning system and servomotor mounted below the test section connected to the model through a 6-component transducer. This control system allows complete synchronization of all events: dynamic pitching frequency and pitching angle, free stream speed, actuator's timing, and all 6-component forces measurements. The wind tunnel is fitted with large windows for extended optical access to permit various non intrusive and minimally intrusive diagnostic, including Femtosecond Laser Electronic Excitation Tagging (FLEET) to be utilized. The experimental program for plasma control requires high-voltage power sources for excitation of the air. This will be achieved with nanosecond and sub nanosecond pulse sources driving new designs of surface electrodes, as well as new dielectric and semiconducting surface structures. The tunnel test section is built with dielectric walls to avoid electromagnetic interactions with the experiments.

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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)**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in peer-reviewed journals:**

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

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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**(c) Presentations**

Number of Presentations: 0.00

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

Received      Paper

**TOTAL:**

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

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

Received      Paper

**TOTAL:**

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

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**(d) Manuscripts**

Received      Paper

**TOTAL:**

Number of Manuscripts:

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**Books**

Received      Book

**TOTAL:**

Received      Book Chapter

**TOTAL:**

**Patents Submitted**

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**Patents Awarded**

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**Awards**

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**Graduate Students**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

**Names of Post Doctorates**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

**Names of Faculty Supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Names of Under Graduate students supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Student Metrics**

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

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

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**Names of Personnel receiving masters degrees**

<u>NAME</u>
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**Names of personnel receiving PHDs**

<u>NAME</u>
<b>Total Number:</b>

**Names of other research staff**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Dan Hoffman	0.30
Nick Tkach	0.12
<b>FTE Equivalent:</b>	<b>0.42</b>
<b>Total Number:</b>	<b>2</b>

**Sub Contractors (DD882)**

**Inventions (DD882)**

**Scientific Progress**

See Attachment

**Technology Transfer**

**DURIP: Transonic Wind Tunnel Modernization for Experimental Investigation of Dynamic Stall in a Wide Range of Mach Numbers by Plasma Actuators with Combined Energy/Momentum Action**

**FINAL REPORT**

**ARO DURIP Grant No.** W911NF-13-1-0328 **Start Date:** 09/01/2013

**PRINCIPAL INVESTIGATOR:** Professor Richard B. Miles, Professor Alexander J. Smits,  
Dr Andrey Yu. Starikovskiy

**LEAD INSTITUTION:** Princeton University – Department of Mechanical & Aerospace Engineering

**PROGRAM OBJECTIVES:**

Funds were requested for deep modernization of the Low-Turbulence Variable Geometry (LTVG) Wind Tunnel at Princeton University. Wind tunnel test section modernization should include the possibility of tests of different types of actuators, including plasma-assisted actuation. The work proposed should result in the new facility for flow control on an oscillating airfoil for dynamic stall regimes in a wide range of Mach numbers and pitching frequencies, including mechanical and plasma concepts.

**PROGRAM RESULTS:**

Princeton University has built a new facility for experimental investigation of dynamic stall in a wide range of Mach numbers by plasma actuators. This facility is based on the Subsonic Variable Speed Plasma (SVSP) blow-down wind tunnel. Support for the instrumentation and modification of this facility has been provided by ARO DURIP funds.

## Wind Tunnel

This is a high speed, low turbulence wind tunnel facility that has been made available as a dedicated facility and is being modified for plasma related experiments (Figure 1).



Figure 1. Subsonic Variable Speed Plasma (SVSP) blow-down wind tunnel.

The tunnel has a cross-section of 250mm x 360(200)mm and has generous optical access. The wind tunnel is equipped with 4 screens flow silencer and the intake diffuser has 1:16 contraction ratio, which allows it to achieve a low-turbulence flat flow field in the working section. The schematics and instrumentation for the Subsonic Variable Speed Plasma (SVSP) Wind Tunnel are shown in Figure 2.

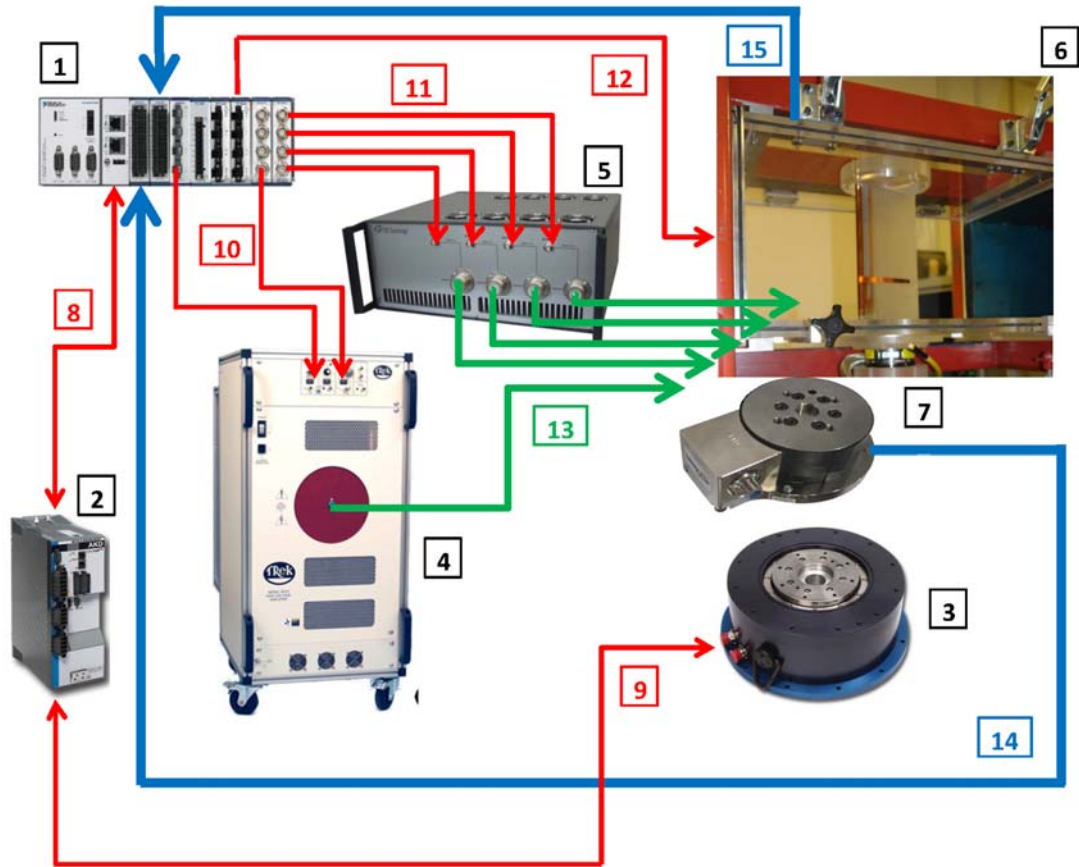


Figure 2. Subsonic Variable Speed Plasma (SVSP) Wind Tunnel schematics and instrumentation. 1 – NI cRIO 9068 control module, including programmable voltage and current sources; 32-ch differential 16-bit analog input modules; 8-ch TTL input/output modules; EtherCAT interface for servomotor control. 2 – servomotor drive. 3 – direct drive Kollmorgen servomotor. 4 – TREK high-voltage amplifier for bias/AC supply. 5 – FID 4-ch pulser. Maximal voltage 36 kV, frequency 20 kHz, pulse duration 15 ns, interchannel jitter less than 100 ps. 6 – wind tunnel. Maximal speed is 180 m/s for small chord models; 100 m/s for large models. 4 screens; 1:16 contraction ratio. 250×360 mm<sup>2</sup> cross-section. 7 – ATI-IA DAQ F/T 6-component transducer. 8 – EtherCAT interface. 9 – servomotor interface. 10 – amplifier control. 11 – FID pulser synchronization. 12 – dynamic control of wind tunnel speed. 13 – high-voltage lines to actuators. 14 – DAQ transducer cable. 15 – Pitot tube and hot wire sensors free-stream velocity data.

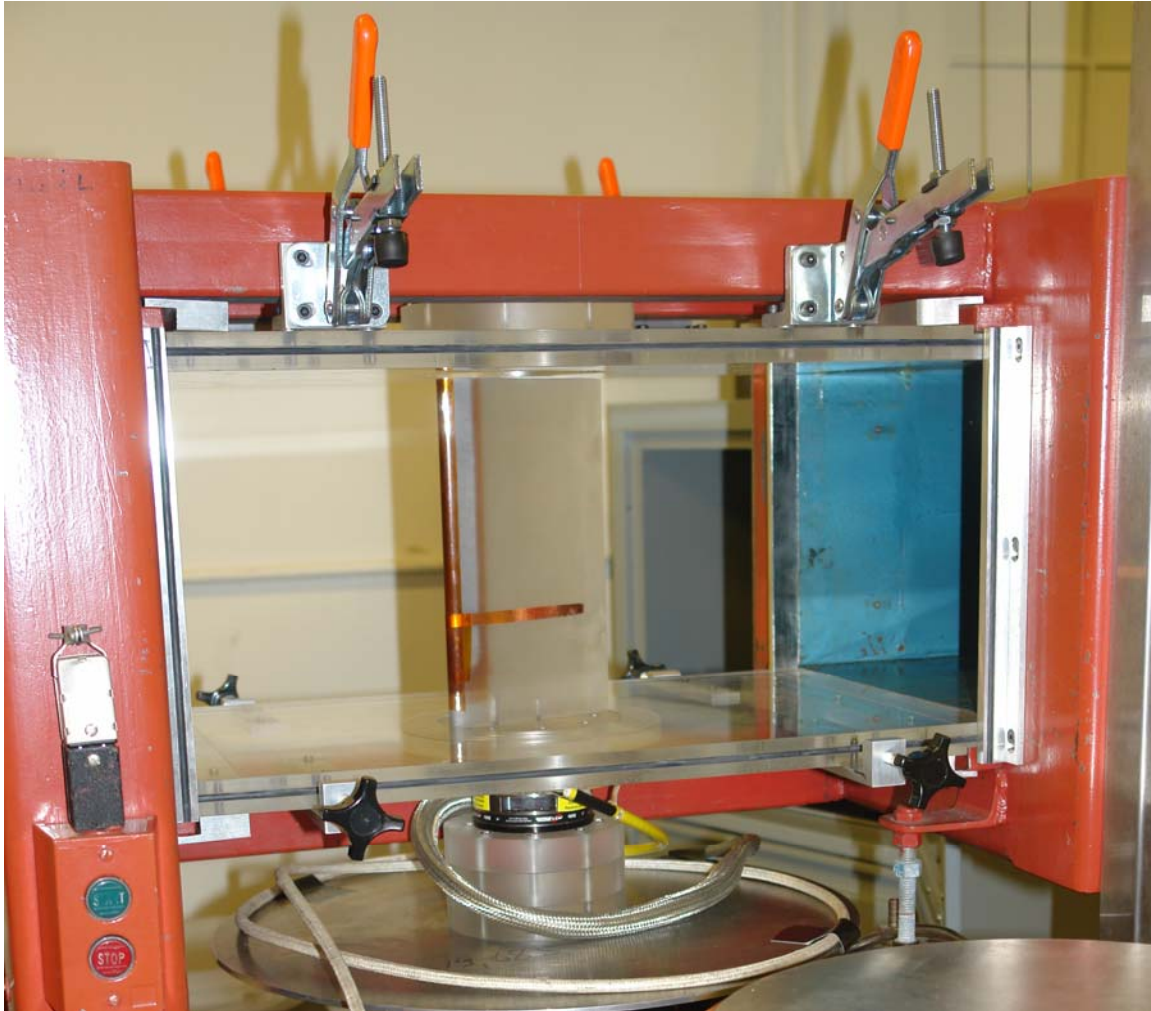


Figure 3. New test section.  $250 \times 360 \times 600 \text{ mm}^3$ . 1-inch solid Plexiglas side walls are removed. The ATI-IA 6-component transducer is directly connected to model. Signal cable has additional screening to reduce the EMI noise in low-voltage lines.

Depending on the motor's blades angle we will be able to change the flow Mach number from deeply subsonic to high-speed regime. Maximal speed is 180 m/s for small chord models; 100 m/s for large models.

The experimental test section has been replaced with a Plexiglas one to avoid electrical sparks between electrodes and conductive walls. The new test section has 1" dielectric walls and can operate with pulsed NS, PS or combined voltage up to 200 kV (Figure 3).

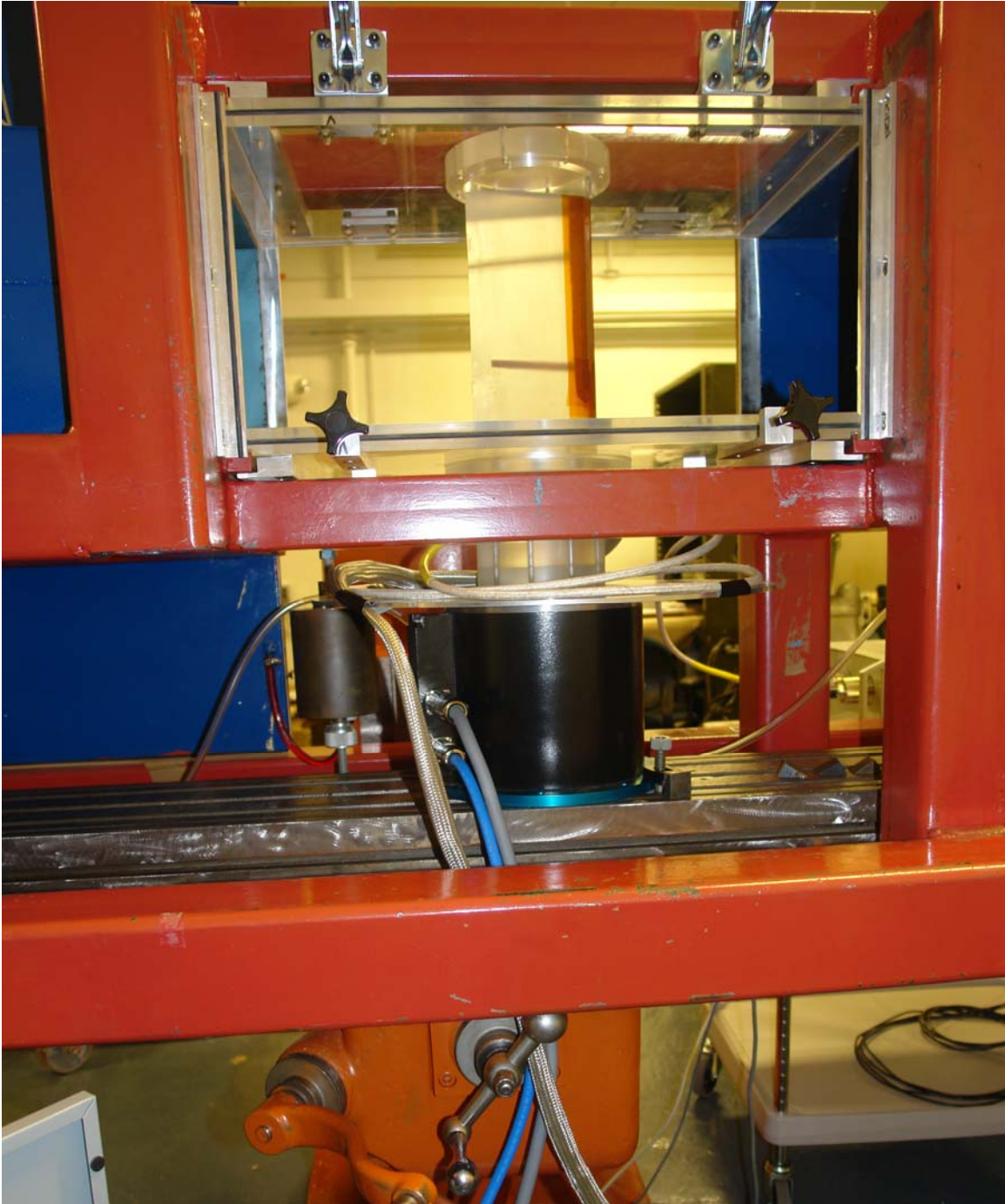


Figure 4. 3D positioning system and Kollmorgen DDR servomotor below the test section. DDR motor is connected to the model through the 6-component ATI-IA transducer.

### **Pitching mechanism**

A new pitching mechanism consists of a direct drive servomotor, equipped with 6-component bridge sensor system. The servomotor is controlled by National Instruments cRIO system

together with all other elements of the experiment – including high-voltage generators and wind tunnel velocity. This system allows complete synchronization of all events: pitching angle, free stream speed, actuator’s timing, and all 6-component forces measurements using ATI-IA DAQ F/T transducers with variable calibrations. The calibration range is from 32 to 660 N full-scale for forces and from 2.5 to 60 Nm for torque. The direct drive servomotor by Kollmorgen has a peak torque of 160 Nm and maximal speed of 250 rpm (Figure 4). Direct control through EtherCAT NI interface from cRIO control module is utilizing LabView SoftMotion feature, which allows programming of all types of periodical motions – including non-harmonic modes.

The wind tunnel speed is controlled by electromechanical actuator and could be synchronized with the model motion in the test section and plasma actuators using NI controller.



Figure 5. FID 4-channel pulser and BNC synchro-generator. The pulser operates in burst mode synchronized with the model pitching by NI interface.

### High-voltage power sources

The experimental program with high-voltage plasma generation requires high-voltage power sources. We will use our FID pulser (4-channels, maximal voltage 35 kV, frequency 30 kHz, pulse length 15 ns, interchannel jitter less than 100 ps) for nanosecond excitation of the gas. This pulser is externally controlled by BNC Model 575 8-channel synchro-source (Figure 5).

Other higher repetition rate pulsers are also available in our laboratory and can be synchronized for the control of shock coalescence. For slow AC actuation and bias our TREK 40 kV amplifier is used together with a Tek AFG3052 waveform generator.



Figure 6. Shielded Faraday's cage for control electronics. From left to right: UPS power supply; 24-V power supply; NI cRIO 9068 real-time control module; Kollmorgen DDR servomotor interface; main control computer.

The wind tunnel, blade pitching system, plasma generators and control system are completely controlled by computers. The main control computer (Intel Core i7 4770S (3.10GHz) 8GB DDR3 2TB HDD) is running NI LabView program which controls the NI cRIO 9068 real-time

control module, including programmable voltage and current sources; 32-ch differential 16-bit analog input modules; 8-ch TTL input/output modules through Ethernet cable (Figure 6).

NI cRIO 9068 real-time control module controls through EtherCAT interface the direct drive servomotor; TREK high-voltage amplifier for bias/AC supply; FID 4-channel pulser; provided 16-bit analog data acquisition for ATI-IA DAQ F/T 6-component transducer; and controls the wind tunnel speed using electromechanical actuator for motor's blades position and dynamics speed measurements using Pitot tube and hot wire sensors free-stream velocity data.

AFOSR DURIP funding has provided \$670,000 for a new, transportable 1 kHz, femtosecond laser and time gated, intensified camera system that will be used in conjunction with this facility to follow the motion of the air at imaging rates of up to one Megahertz by Femtosecond Laser Electronic Excitation Tagging (FLEET). Figure 7 shows the laser on the transportable optical table.



Figure 7. The laser system for Femtosecond Laser Electronic Excitation Tagging (FLEET)

## **Conclusions**

Princeton University has built a new facility for experimental investigation of dynamic stall in a wide range of Mach numbers by plasma actuators. This facility is based on the Subsonic Variable Speed Plasma (SVSP) blow-down wind tunnel, which is able to operate in a wide range of gas speed up to 180 m/s with a test section designed for high-voltage experiments up to 200 kV. Maximal pitching speed for the model is ~250 rpm.

The completion of the tunnel now provides a versatile facility for detailed experimental investigations of the effects of plasma actuators with energy and/or momentum addition on dynamic stall over a wide range of Mach numbers.

## **Acknowledgements**

Support for the instrumentation and modification of this facility has been provided by ARO DURIP funds.